SPhN seminar, Orme des Merisiers, 17th February, 2017

Penning-trap mass spectrometry of exotic radionuclides with ISOLTRAP

Vladimir Manea

CERN, Geneva, Switzerland

Thanks to …

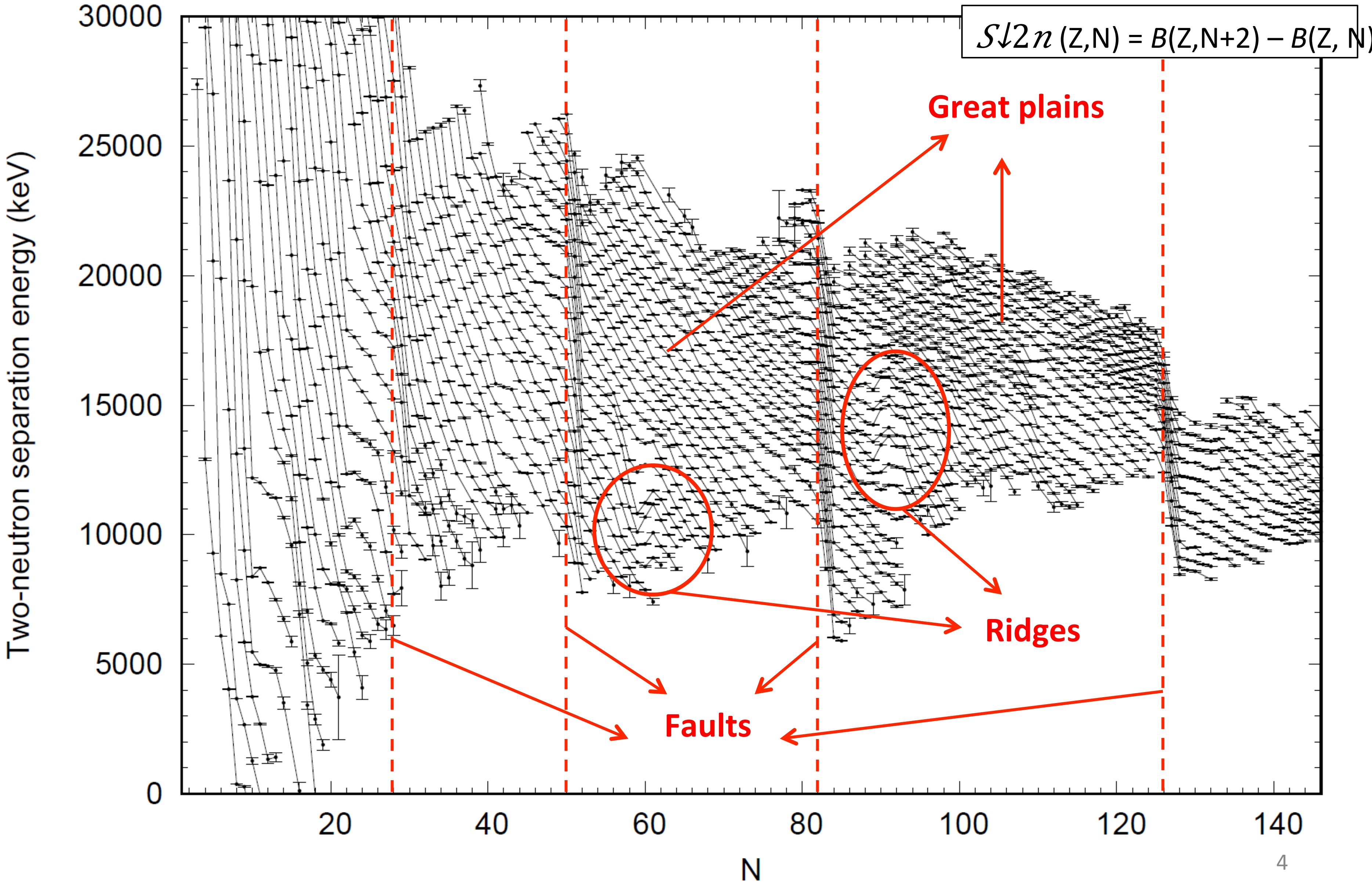
Andree Welker, Maxime Mougeot, Frank Wienholtz, Dinko Atanasov, Jonas Karthein, Anatoly Barzakh, Melanie Delonca, João Pedro Ramos, Sebastian Rothe, Jürgen Kluge

… for some of the materials shown here

Outline

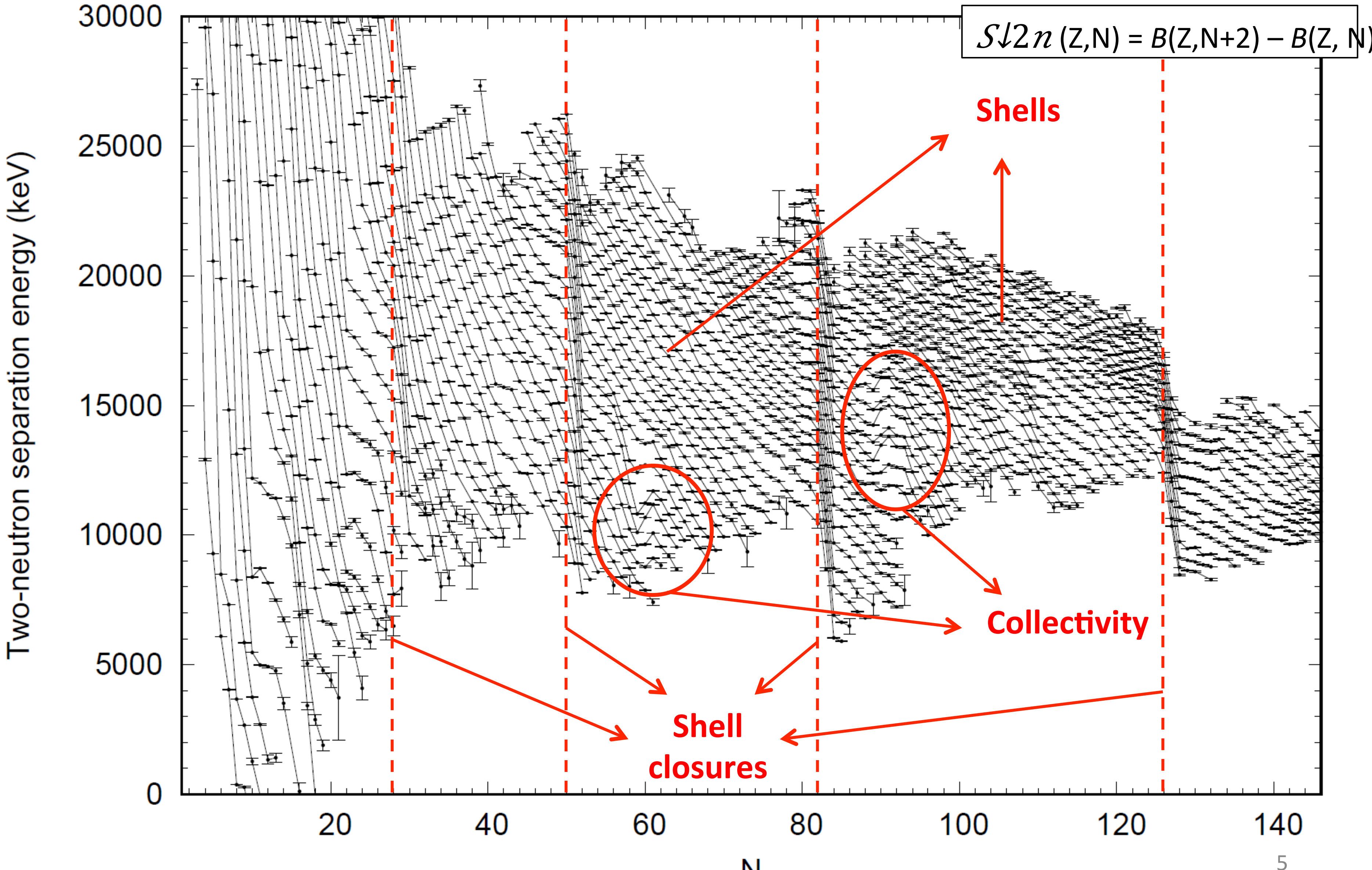
- Principles of Penning-trap mass spectrometry
- ISOLDE and ISOLTRAP
- Results
- Perspectives

Morphology of the mass surface



M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

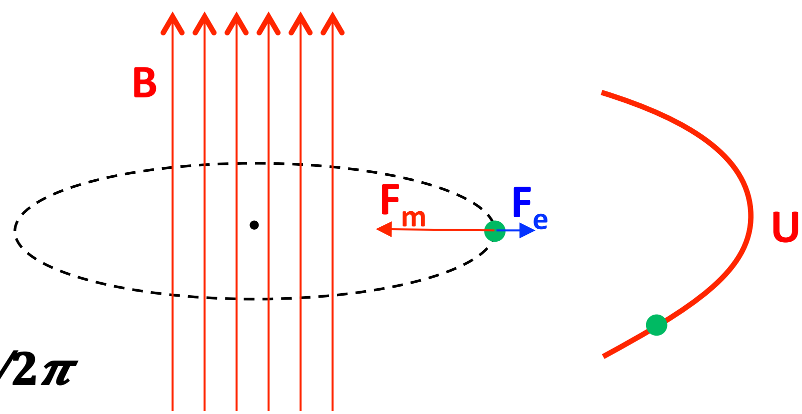
Morphology of the mass surface



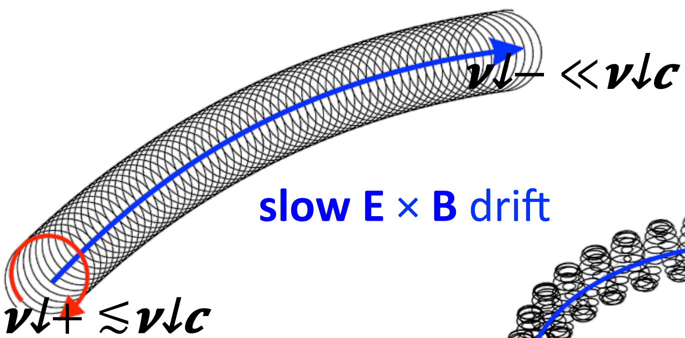
M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

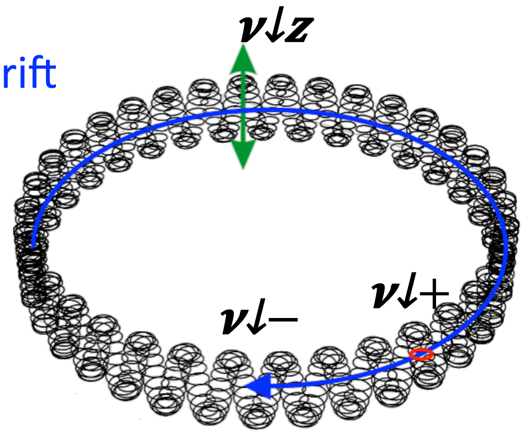
Principles of Penning-trap mass spectrometry

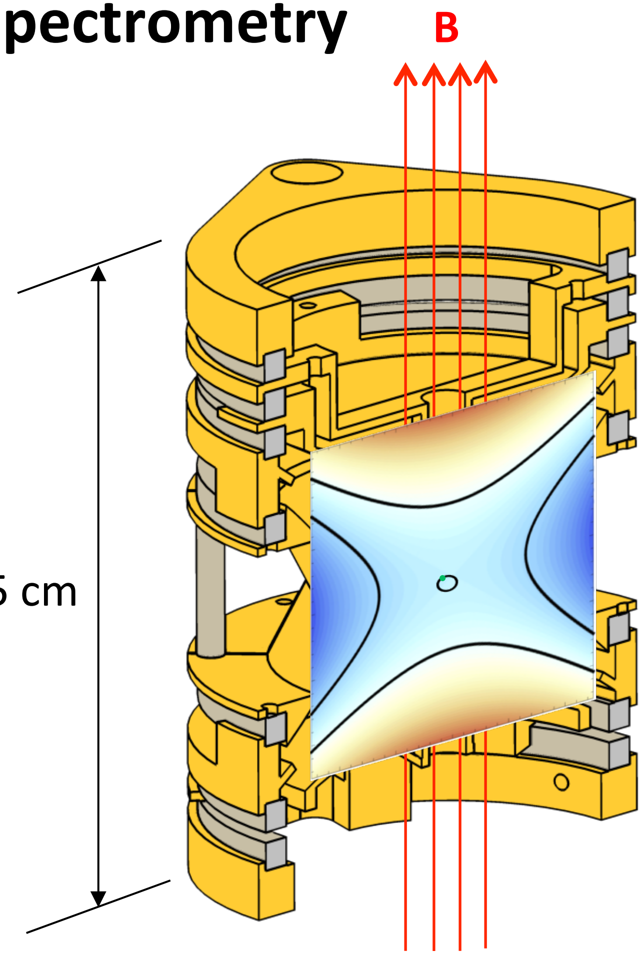
Principles of Penning-trap spectrometry



$\nu_c = qB/2\pi m_{ion}$



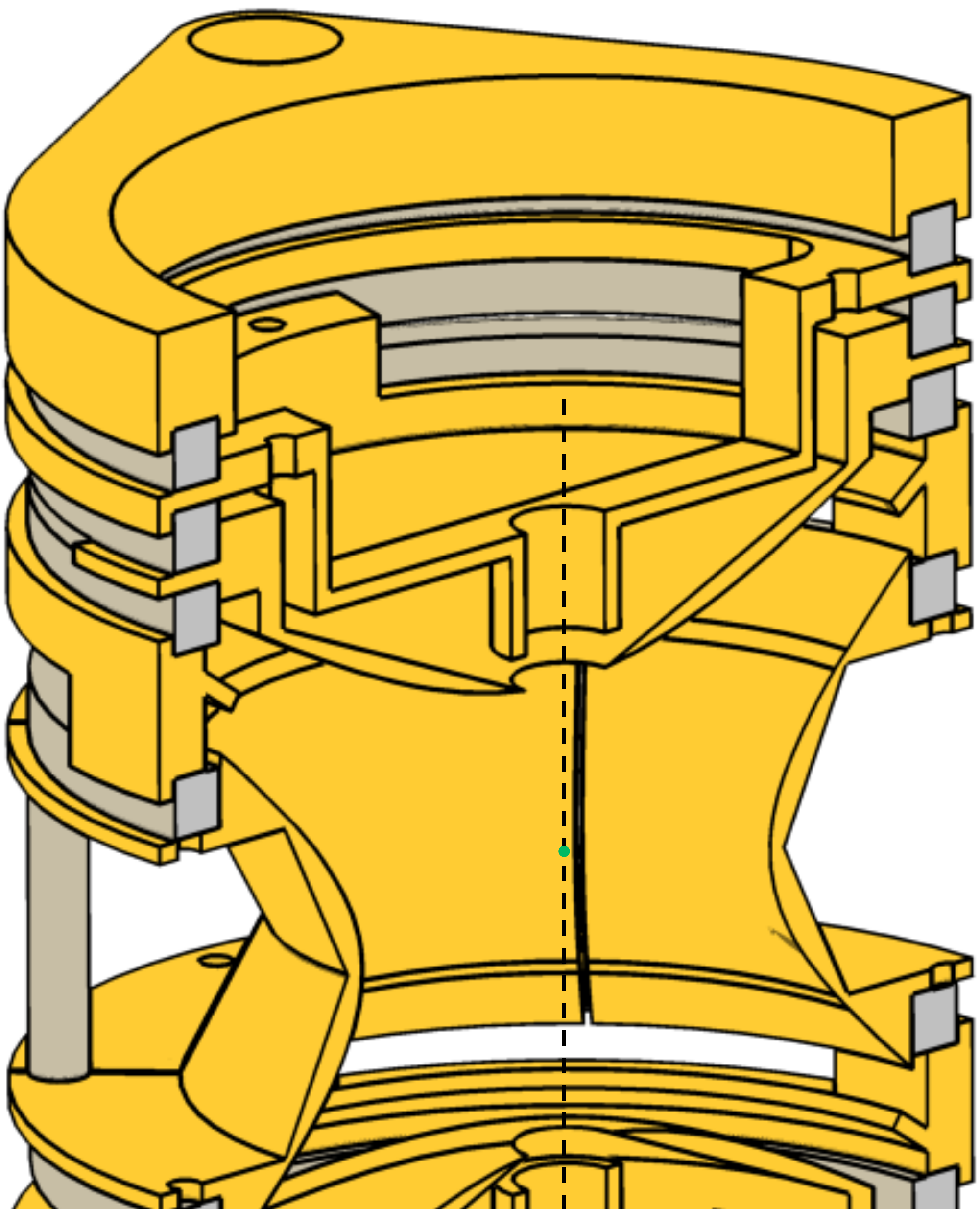


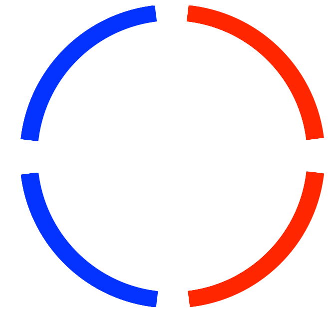


The crucial relation:

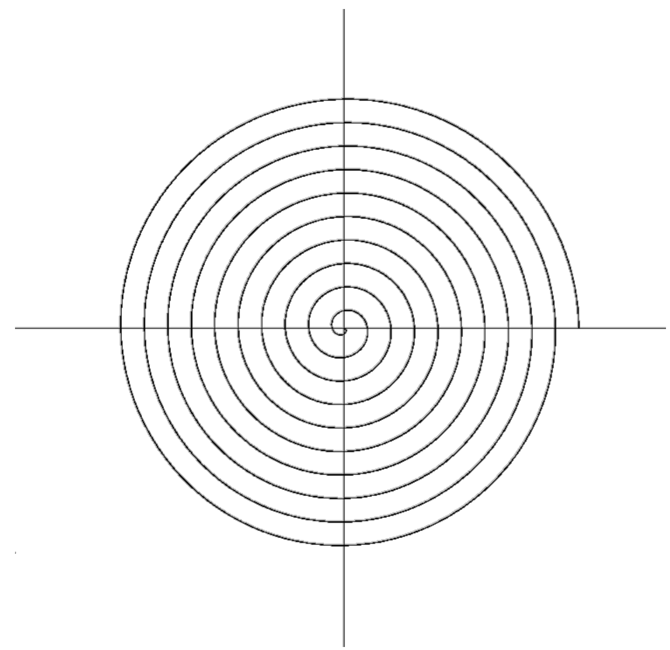
$$\nu_+ + \nu_- = \nu_c$$

Principles of Penning-trap spectrometry

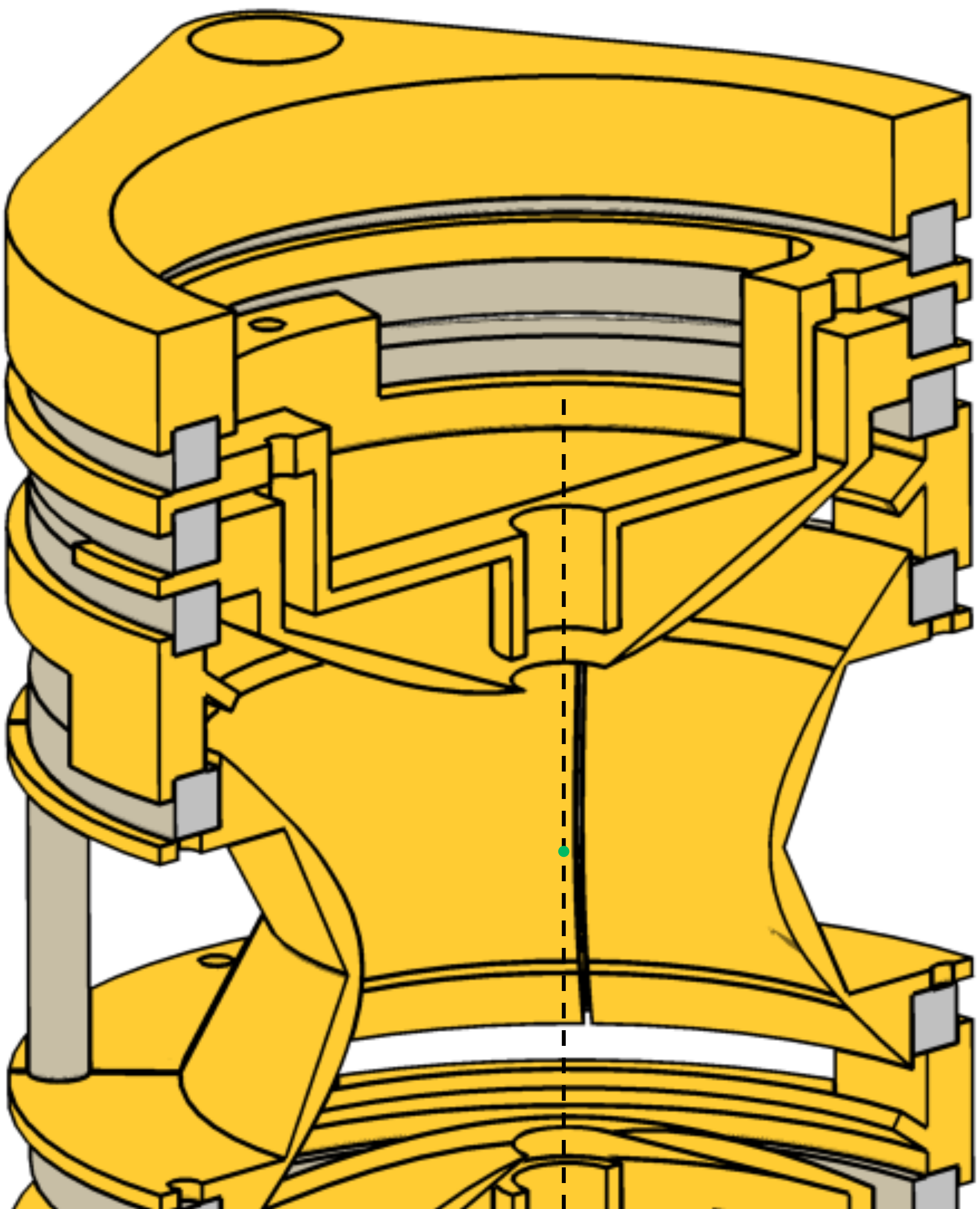


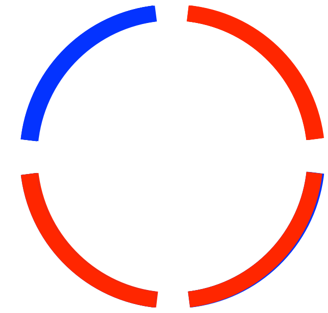


Dipole excitation at ν_+



Principles of Penning-trap spectrometry

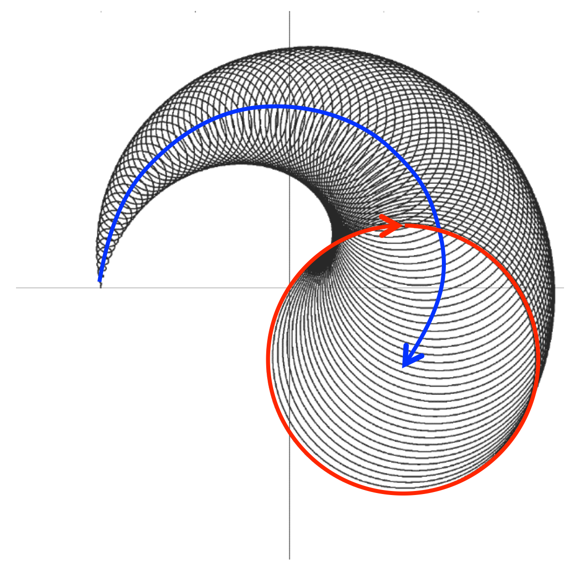




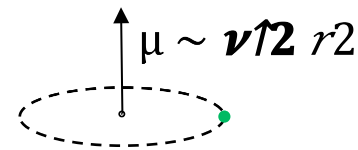
Quadrupole excitation

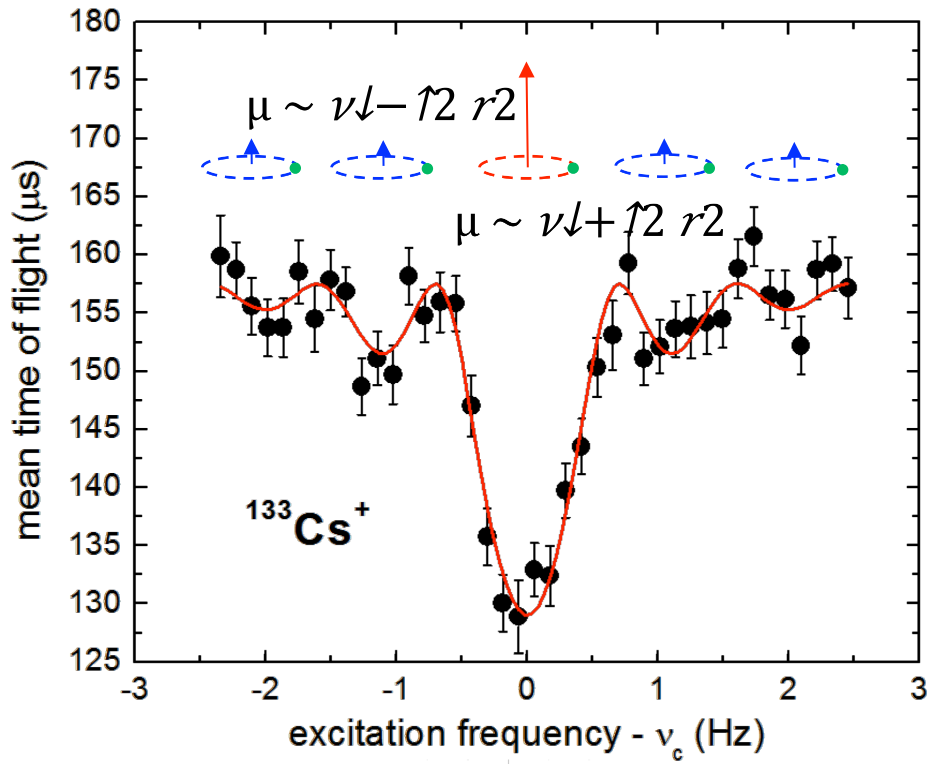
Dipole excitation at ν_-

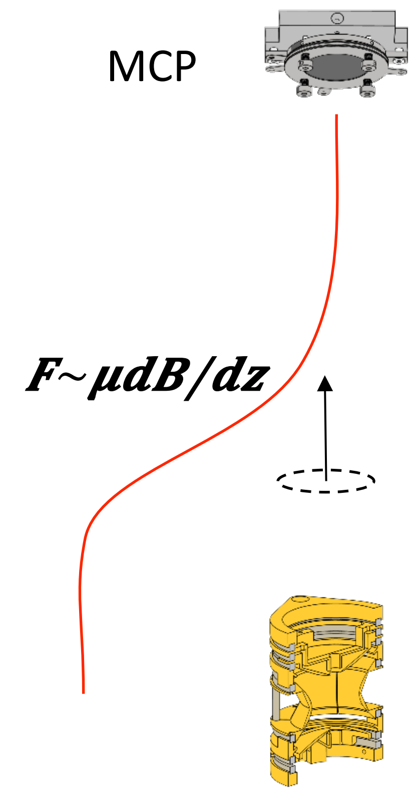
Quadrupole excitation at $\nu_- + \nu_+ = \nu_c$

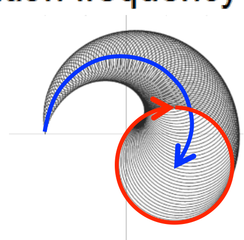


Principles of Penning-trap spectrometry





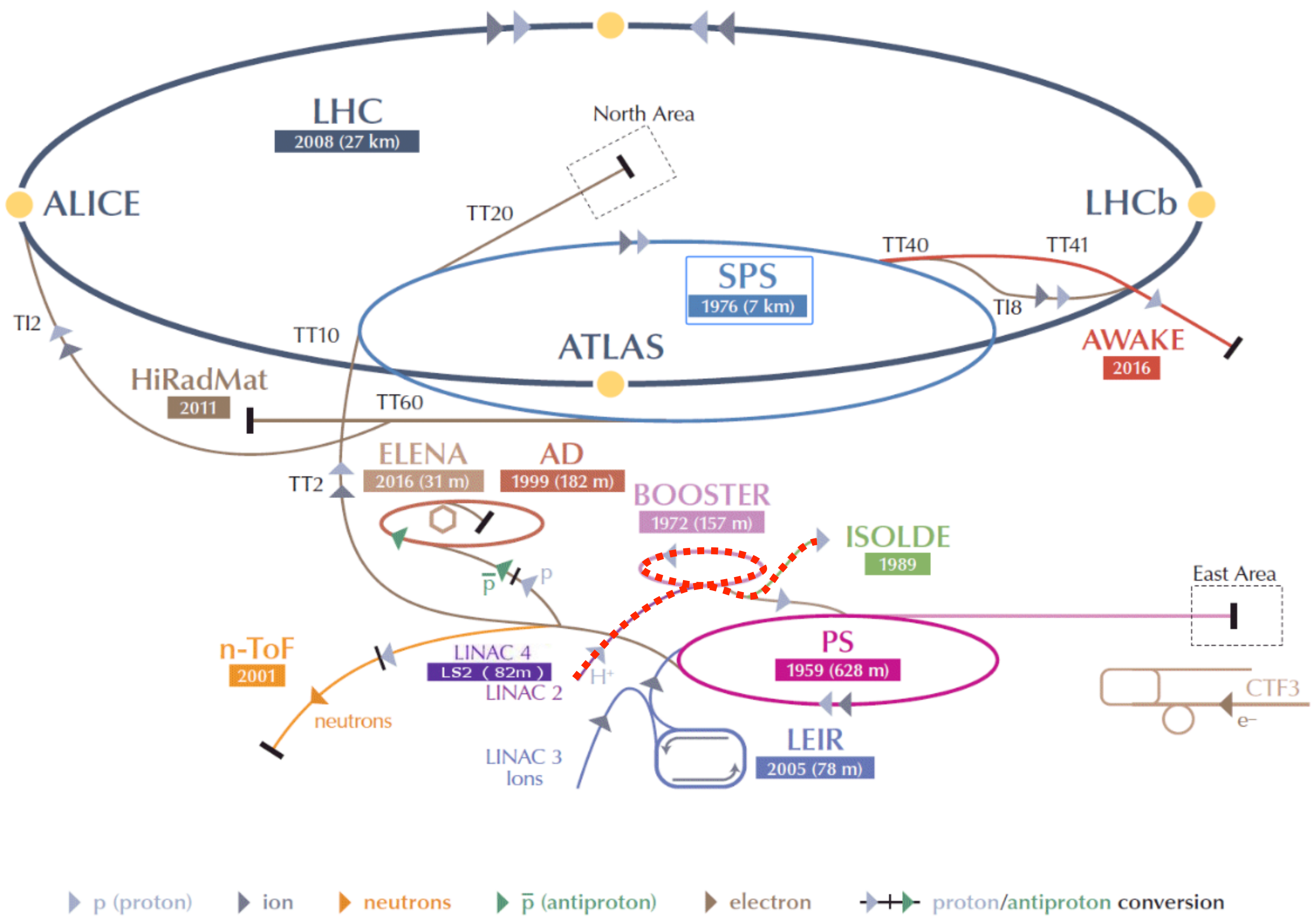




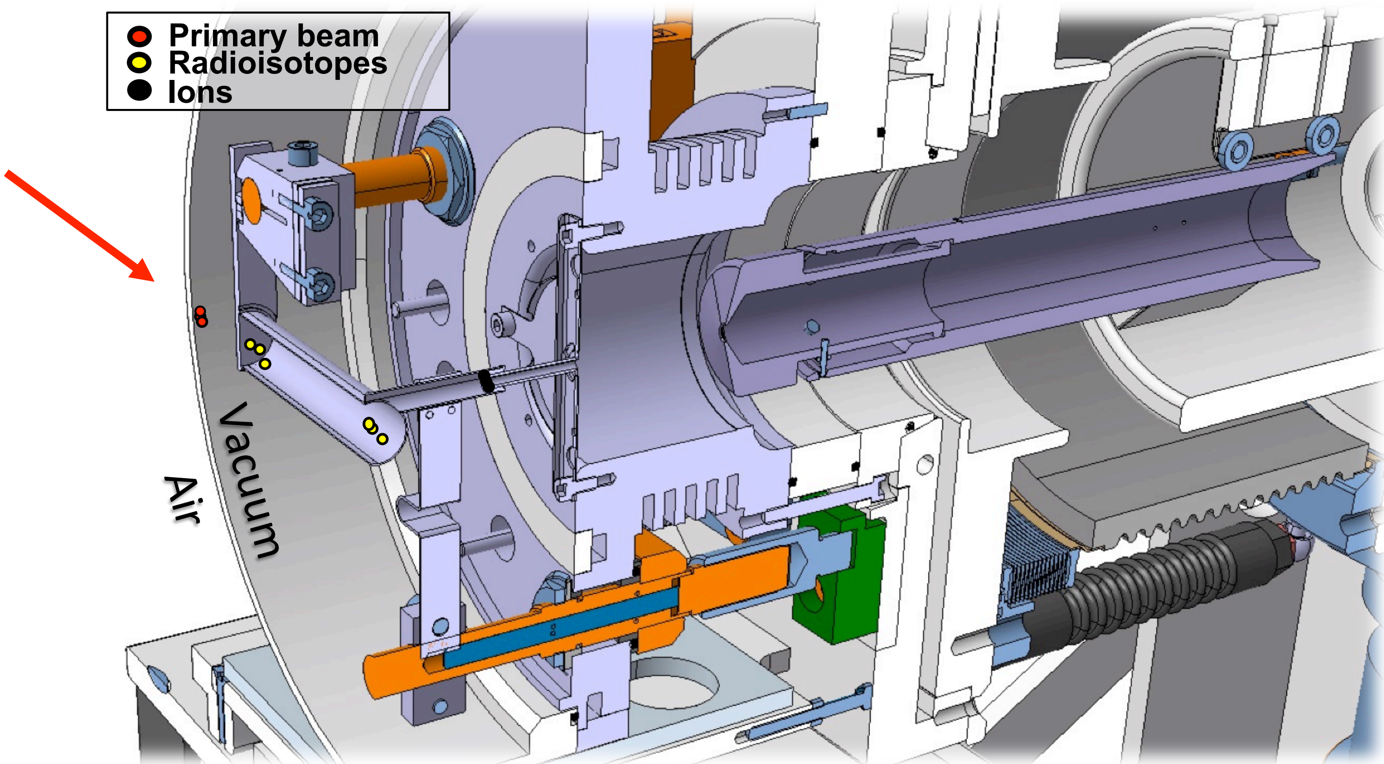
$$\nu_c = qB/2\pi m_{ion}$$

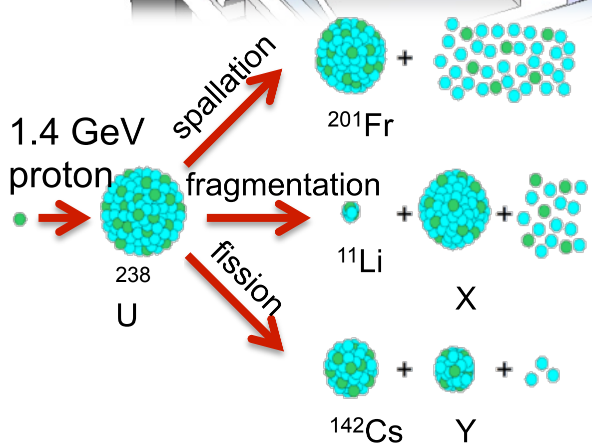
ISOLDE and ISOLTRAP

ISOLDE@CERN


LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
BOOSTER
1972 (157 m)
ISOLDE
1989
TT2
p̄
p
East Area
n-ToF
2001
LINAC 4
LS2 (82m)
LINAC 2
H+
PS
1959 (628 m)
CTF3
e–
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion

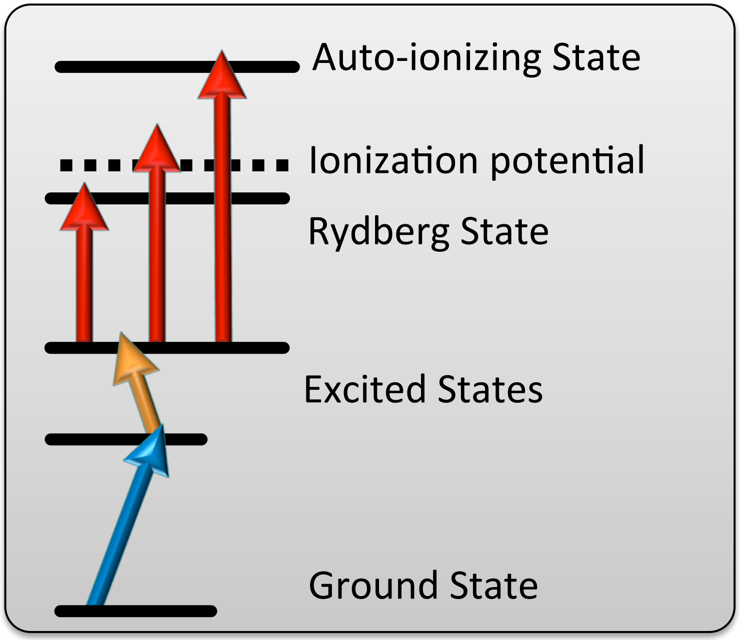
ISOL beams

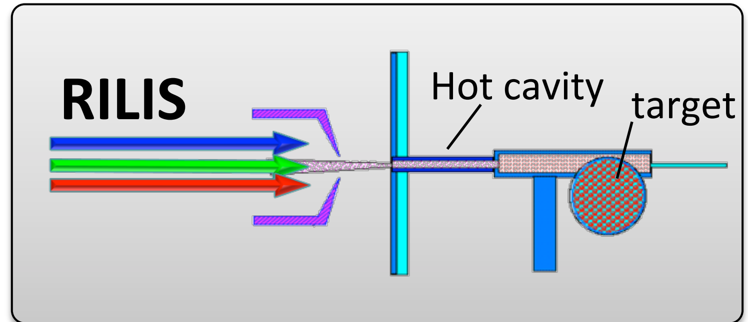




- ➢ Low energy beam
- ➢ Excellent optical quality
- ➢ Slow extraction (>100 ms)
- ➢ Unfavorable chemical properties lead to "production gaps"

The Resonance Ionization Laser Ion Source (RILIS)

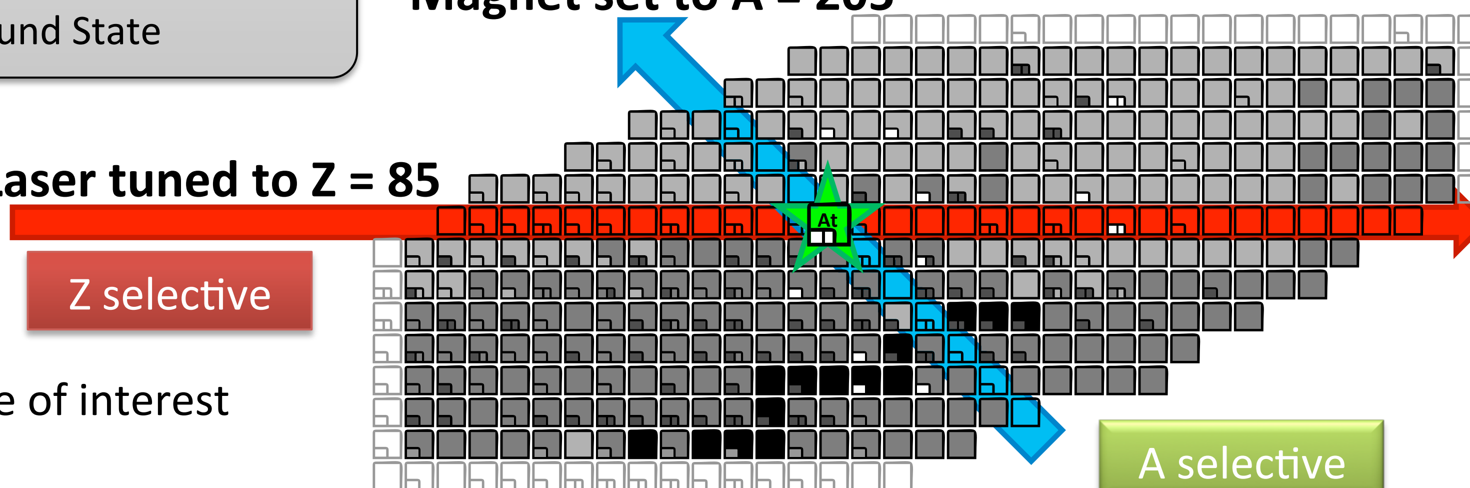




Laser ion source

Magnet set to A = 205

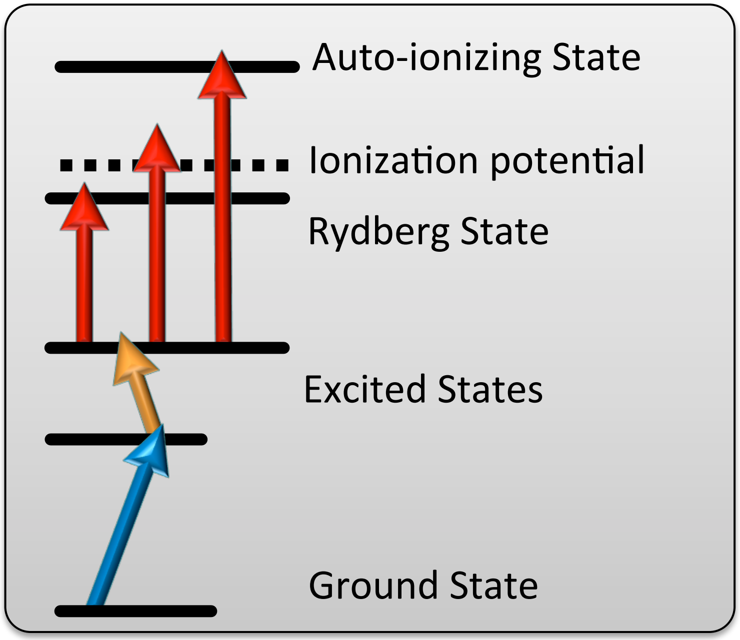
Laser tuned to Z = 85

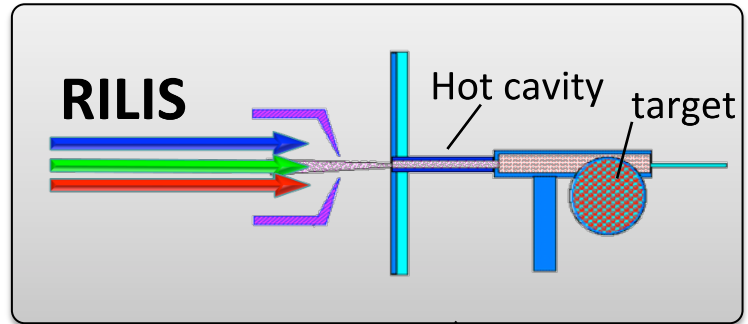


Isotope of interest

Slide courtesy of Sebastian Rothe

The Resonance Ionization Laser Ion Source (RILIS)



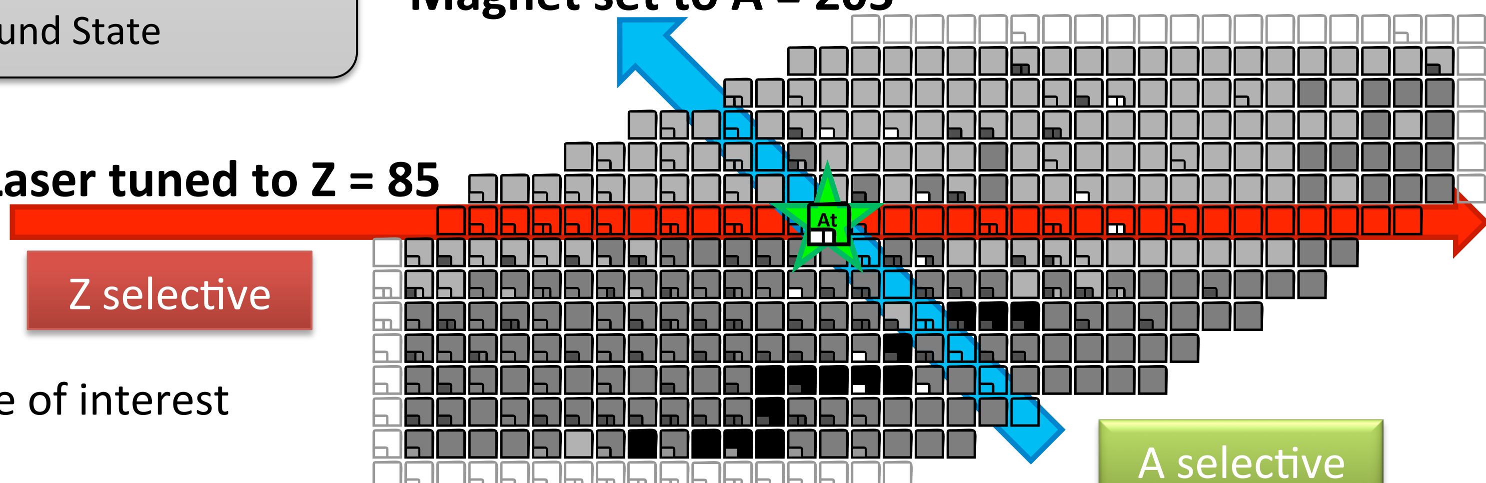


Laser ion source

IS and HFS probe

Magnet set to A = 205

Laser tuned to Z = 85



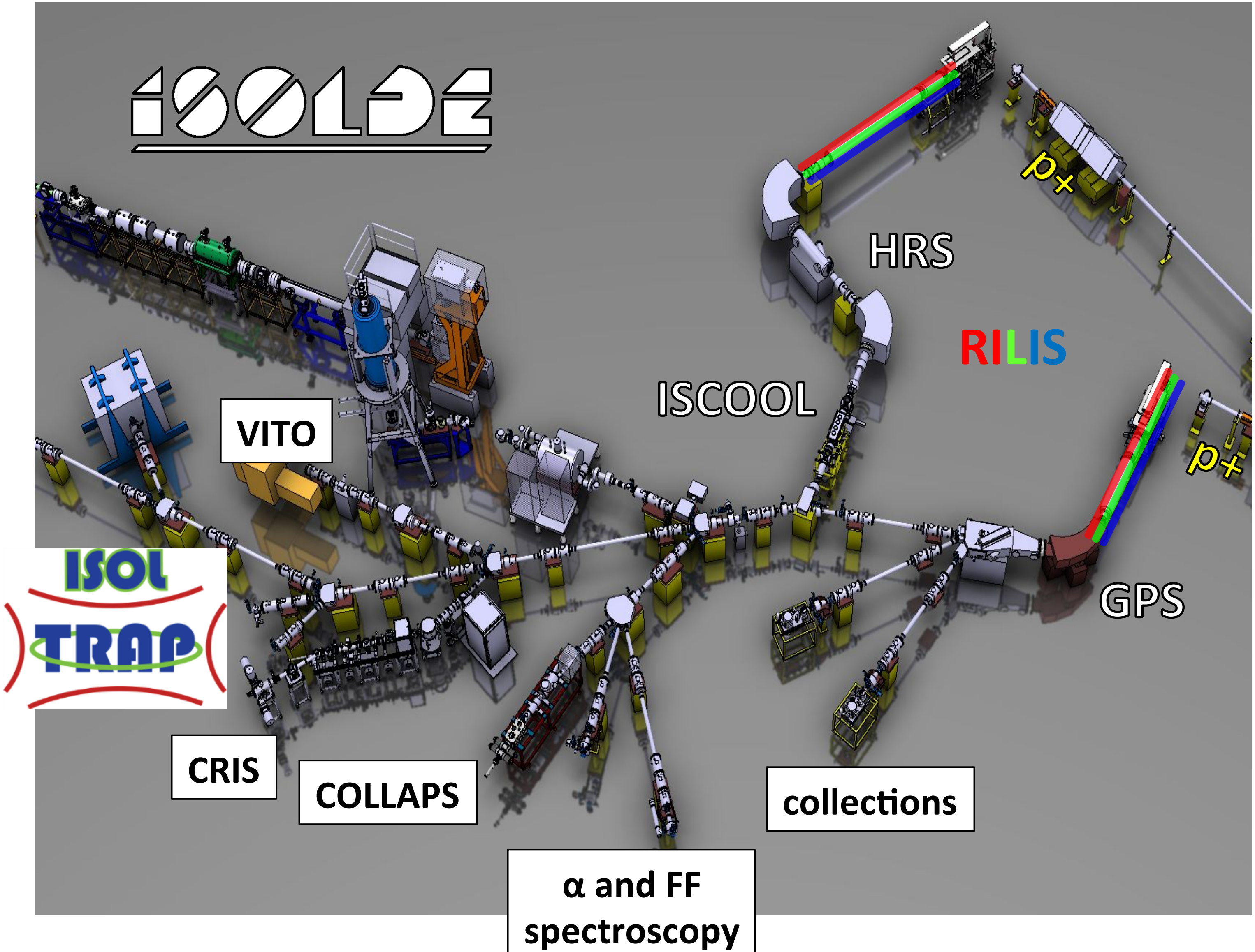
Z selective

A selective

Isotope of interest

Slide courtesy of Sebastian Rothe

ISOLTRAP@ISOLDE



30 years of ISOLTRAP

August 1986

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHENOMENON OF SITE-CHANGING COLLISIONS

G. Bollen[1], H.-J. Kluge[1-2], L. Schweikhard[1]

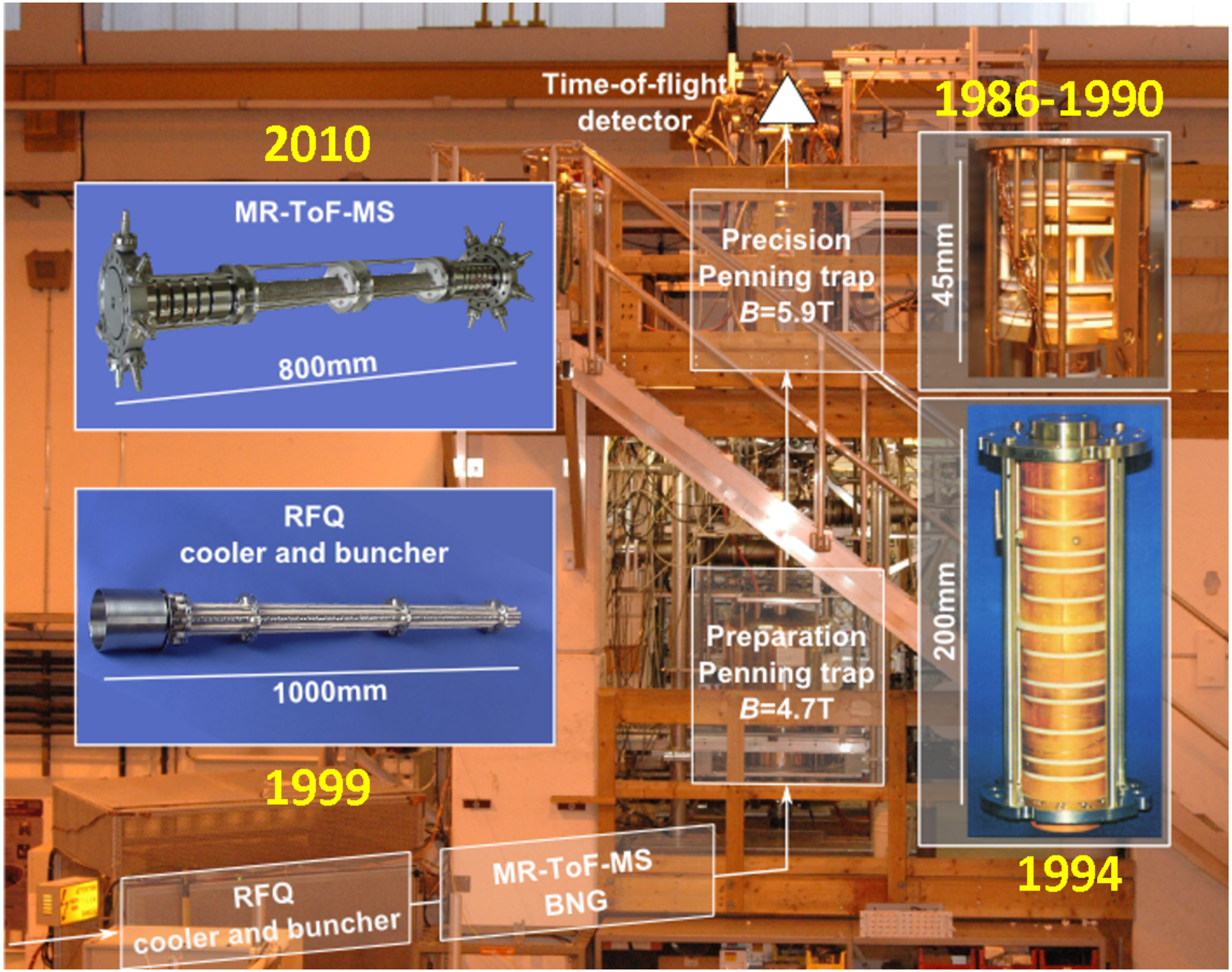
[1]Institut für Physik, Universität Mainz, D-6500 Mainz, Fed. Rep. Germany
[2]CERN/ISOLDE, CH-1211 Geneva 23, Switzerland

Abstract. We have observed the phenomenon of site-changing collissions by bombarding Re and Pt foils with 60 keV Ba ions. The foil was heated after implantation to temperatures sometimes higher than the melting point of Pt and the evaporating ions were detected and mass-separated by time of flight. Only potassium was observed irrespective of the Ba^+ beam intensity. This phenomenon might be explained by site-changing collissions or by a new Barium-Snapper model.

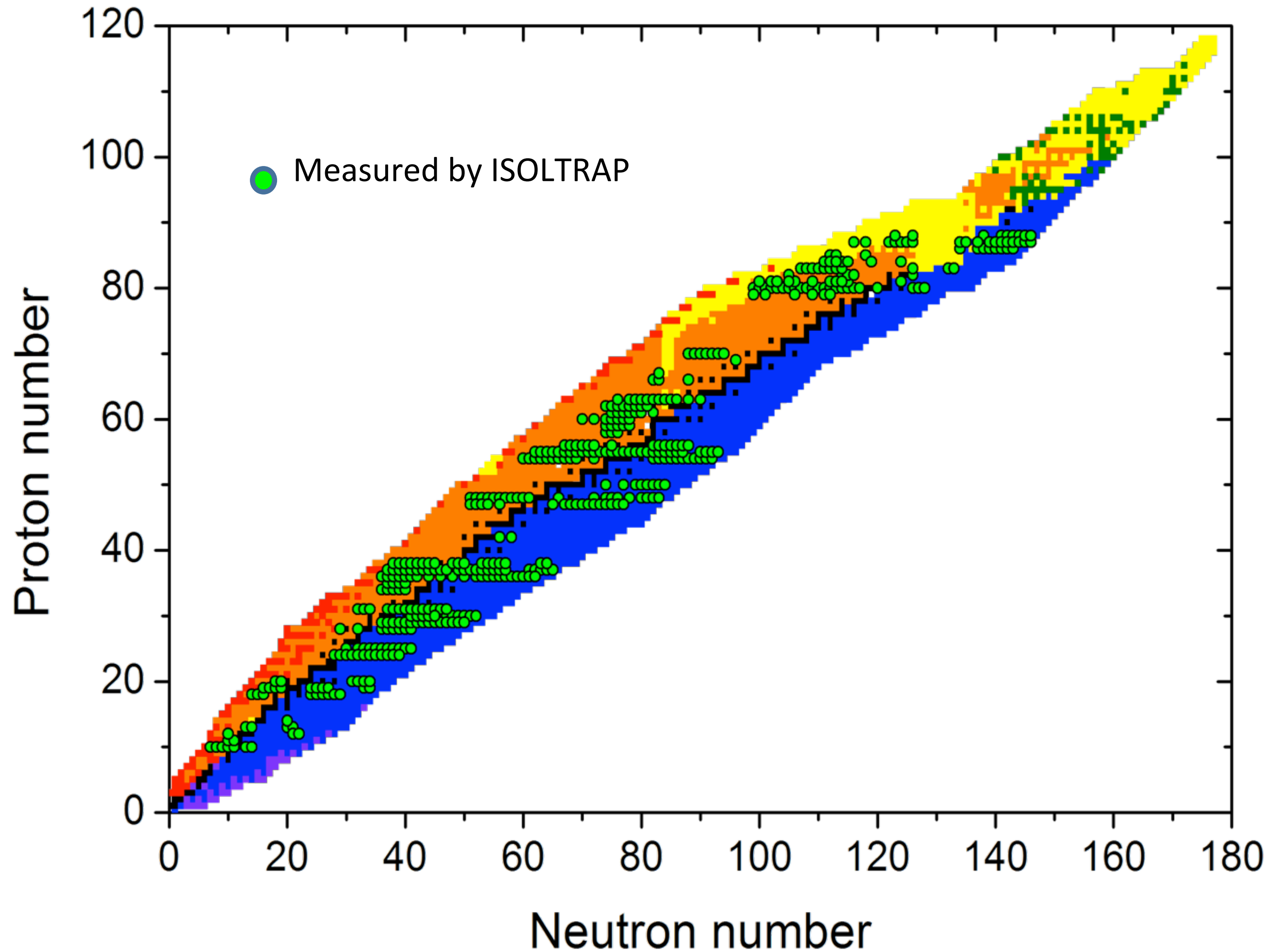
Submitted to Physics Tonight
Section: Non-reproducible Results
28 August 1986

June 1987

ISOLTRAP mass spectrometer

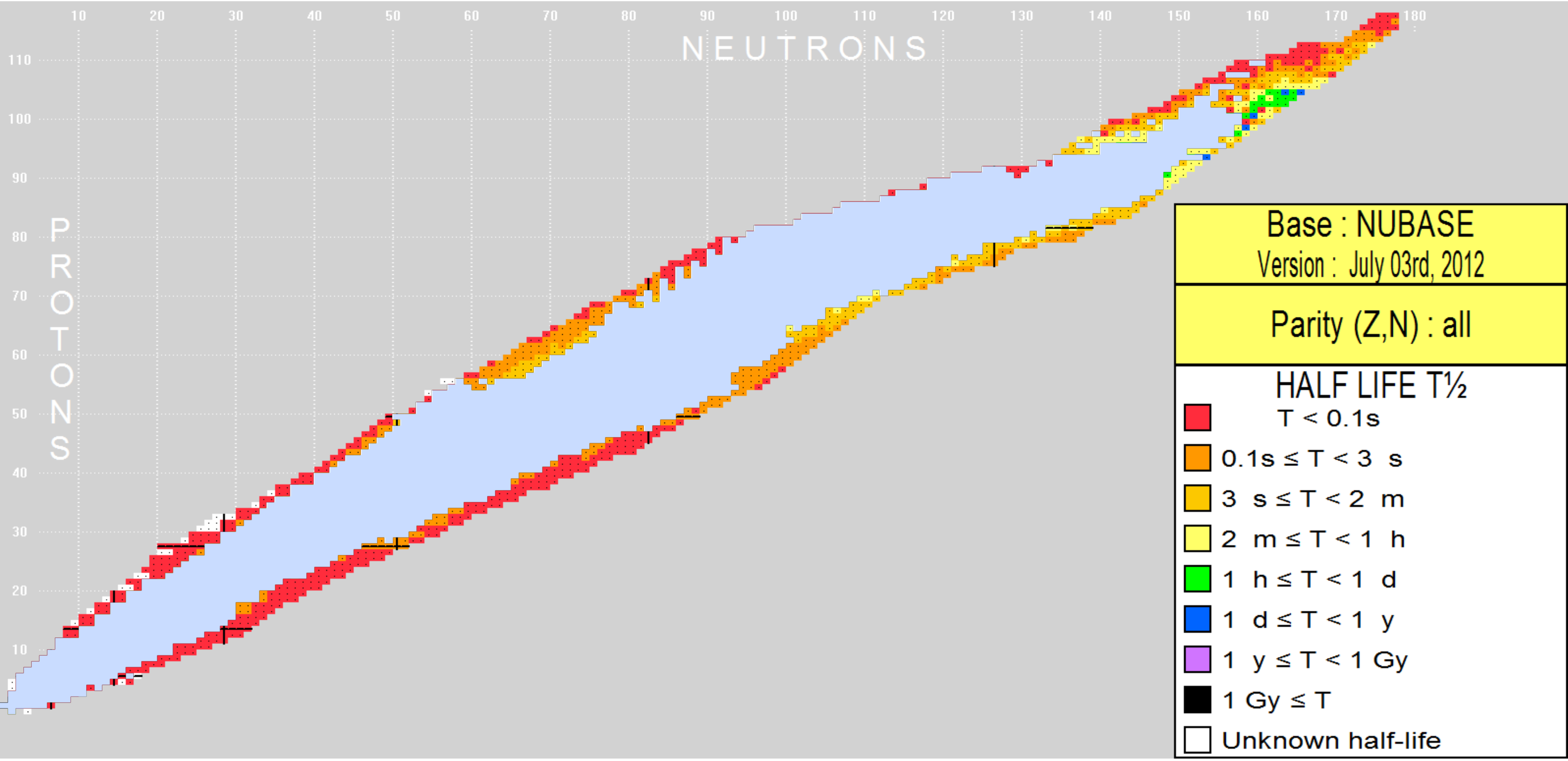


Nuclides measured by ISOLTRAP



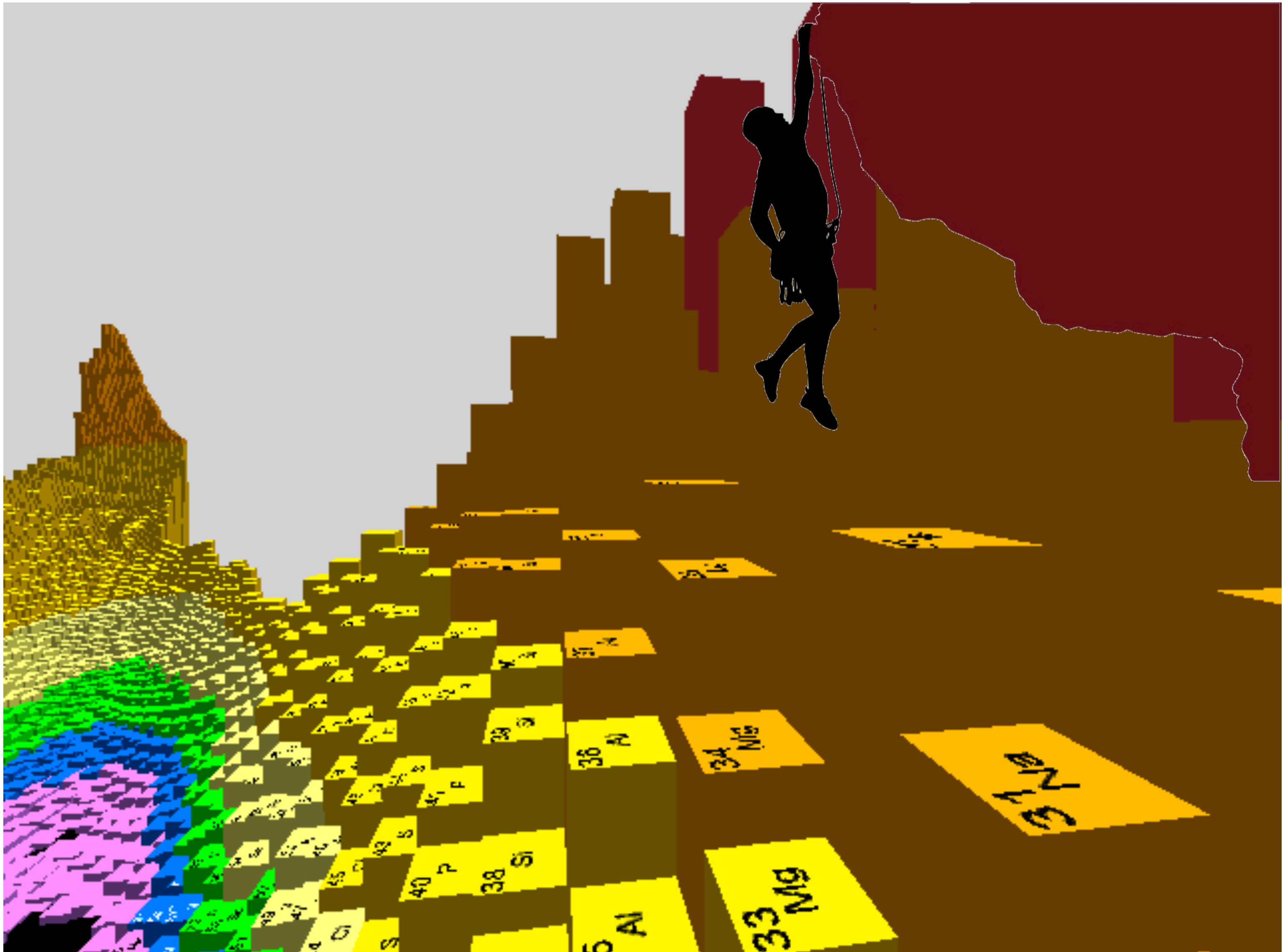
What we're fighting on today

- The nuclides of unknown mass.



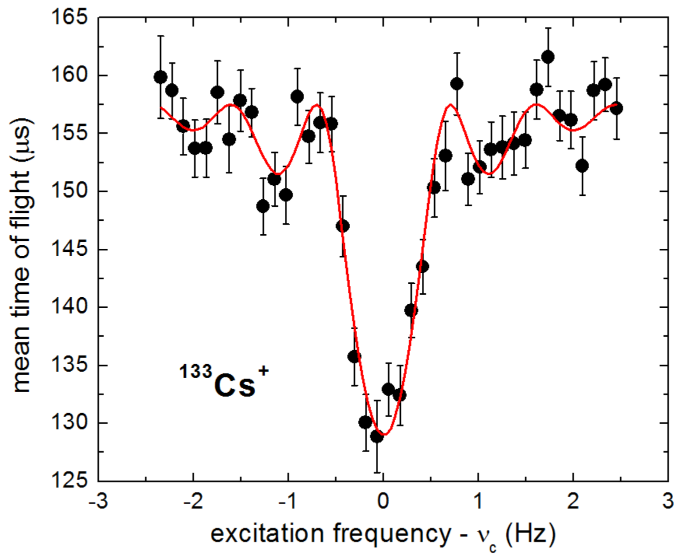
G. Audi *et al.*, Chinese Phys. C **36**, 1157 (2012).

What we’re fighting on today

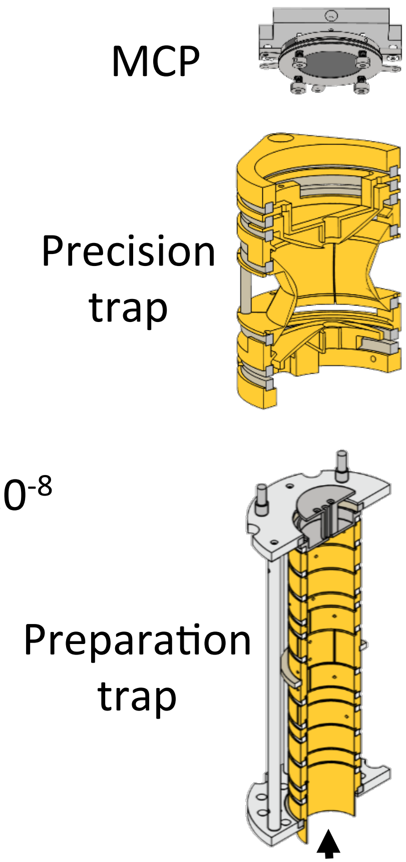


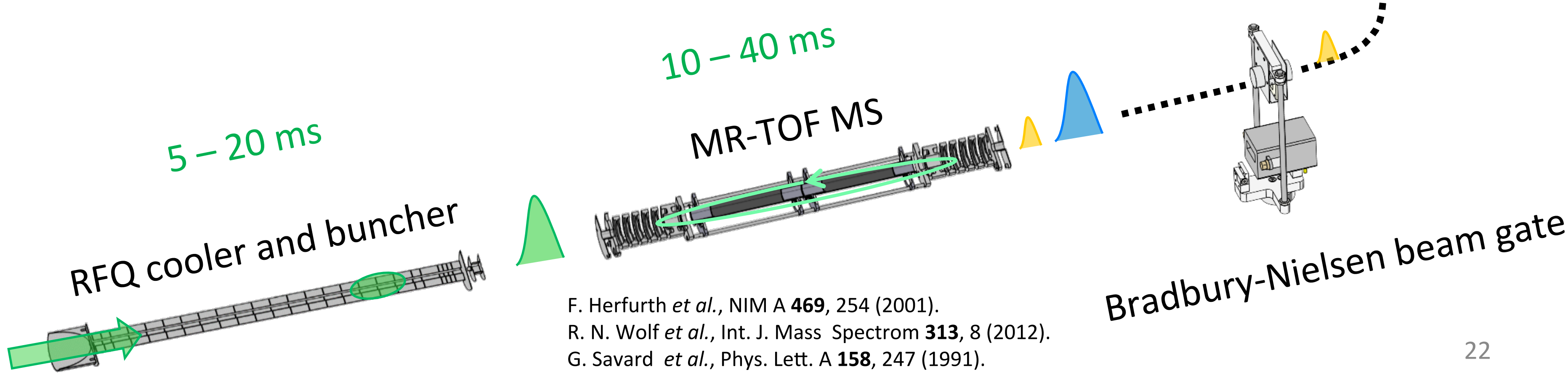
G. Audi *et al.*, Chinese Phys. C **36**, 1157 (2012).

ISOLTRAP spectrometer



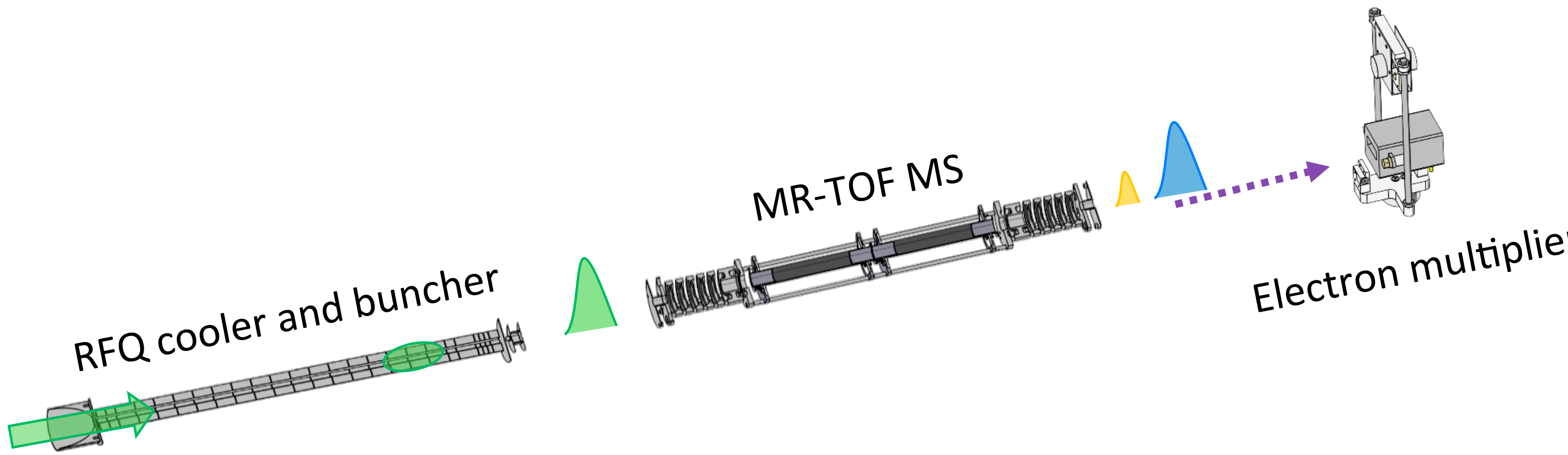
Yield > 1000 / s
Half-life > 50 ms
Precision ~ 2×10^{-8}



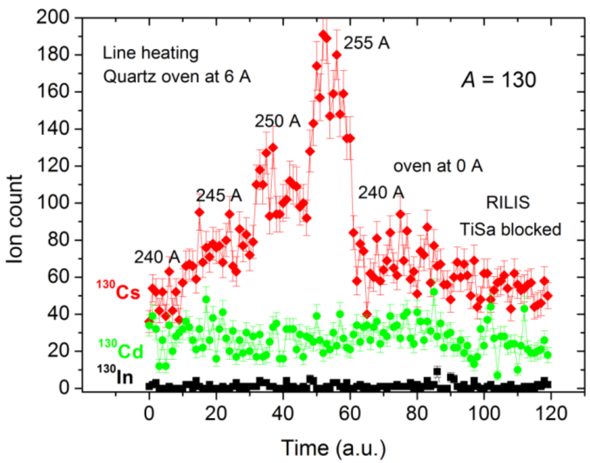


F. Herfurth *et al.*, NIM A **469**, 254 (2001).
R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012).
G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).

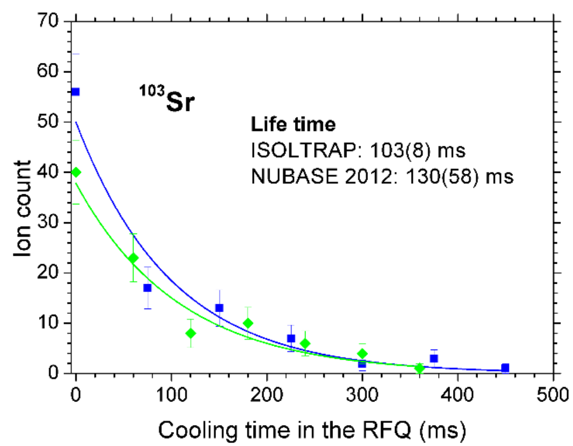
Multi-reflection time-of-flight mass spectrometer



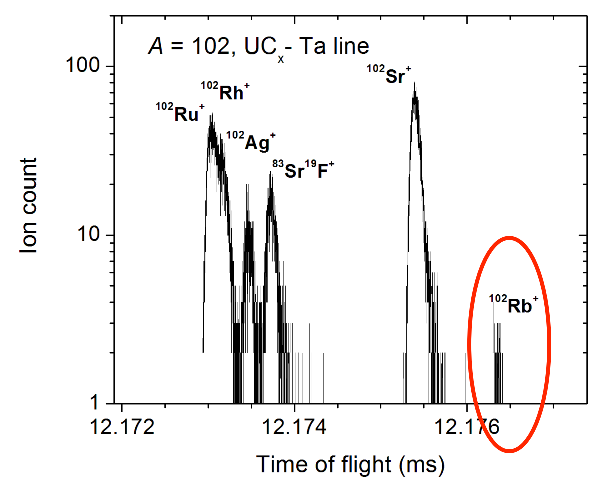
Yield studies



Time-structure studies

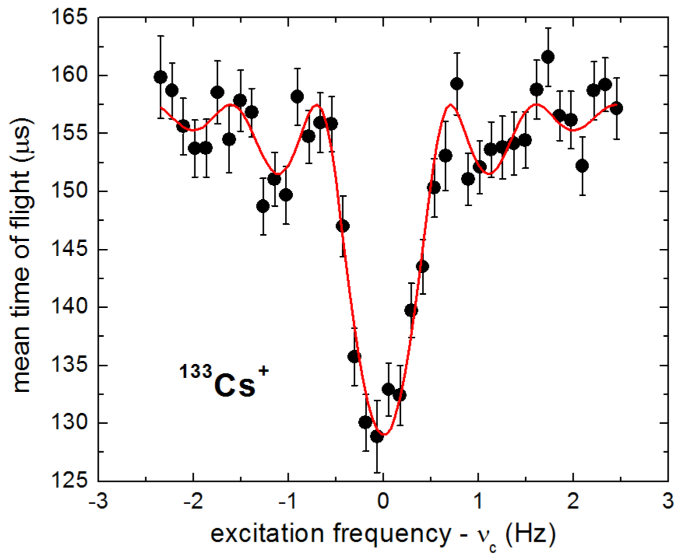


Mass measurements



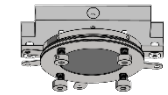
R. Wolf *et al.*, IJMS **349-350**, 123 (2013).
R. Wolf *et al.*, NIMB **376**, 275–280 (2016).

ISOLTRAP spectrometer



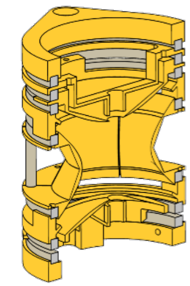
Yield > 1 / s
Half-life > 10 ms
Precision ~ 2 × 10^{-7}

MCP



50 – 1200 ms

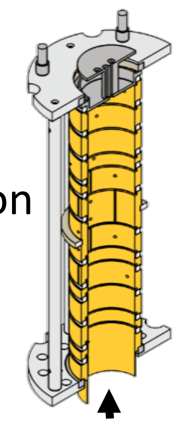
Precision trap

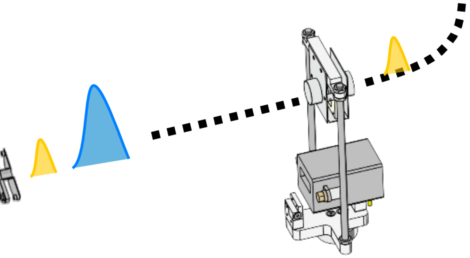


Yield > 1000 / s
Half-life > 50 ms
Precision ~ 2 × 10^{-8}

50 – 200 ms

Preparation trap

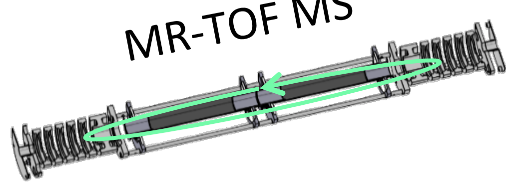




Bradbury-Nielsen beam gate

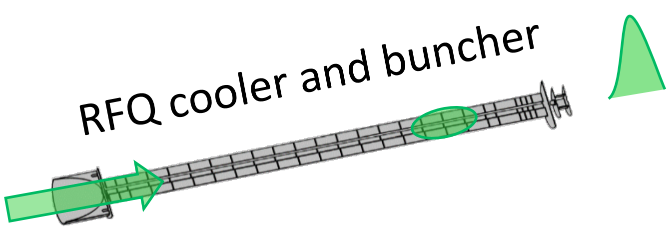
10 – 40 ms

MR-TOF MS



5 – 20 ms

RFQ cooler and buncher



F. Herfurth *et al.*, NIM A **469**, 254 (2001).
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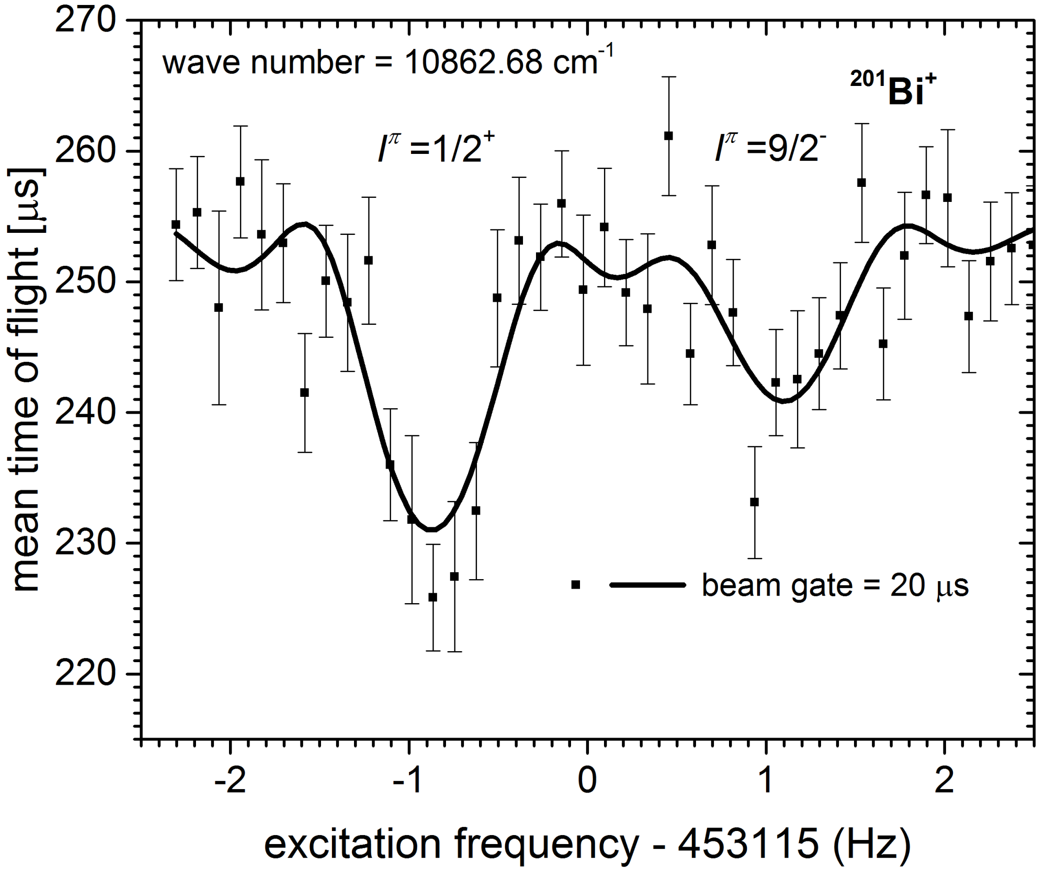
G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).

Effect of contamination



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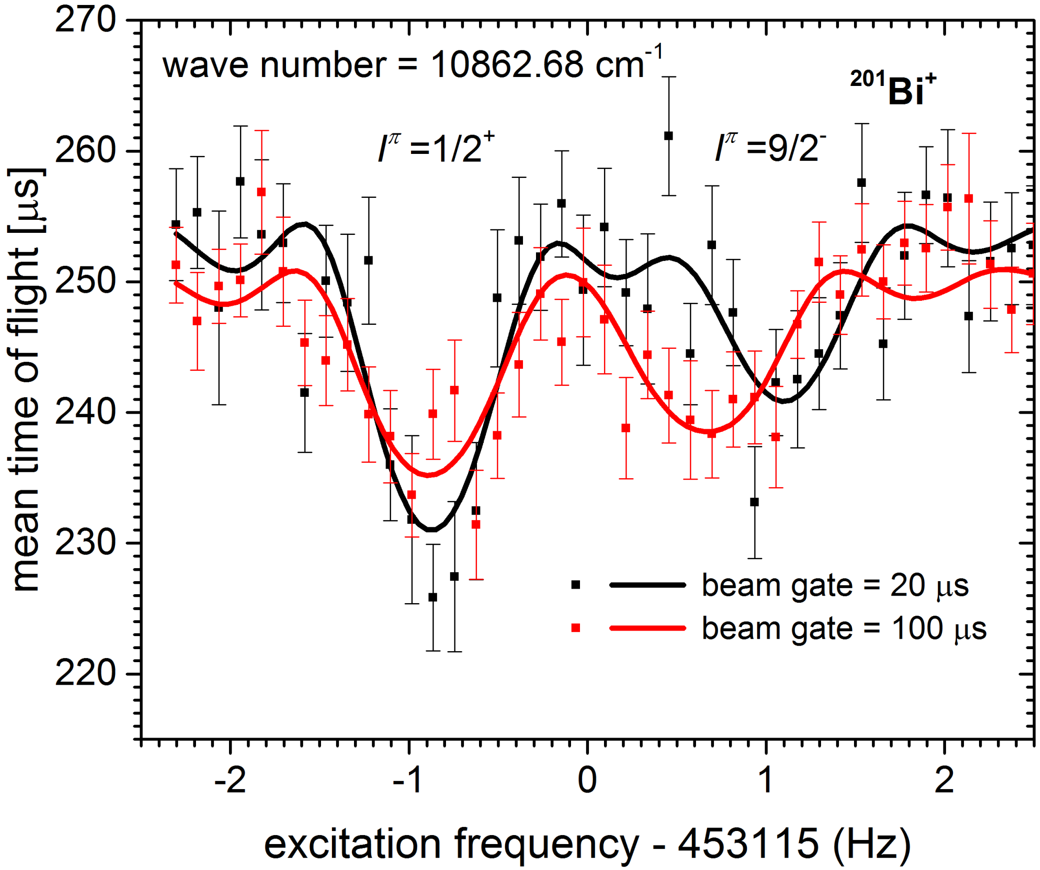
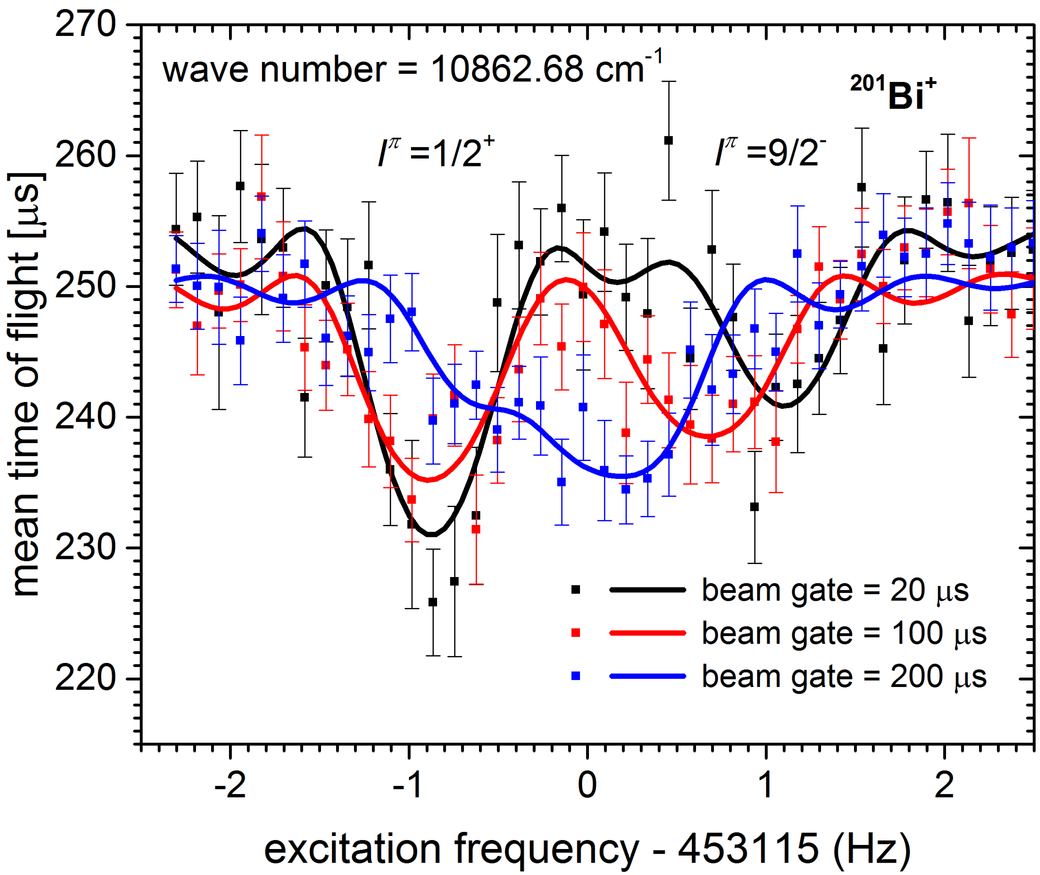


- Ions of different masses mutually perturb their resonance frequency $\nu_+ + \nu_- \neq \nu_c$

Effect of contamination

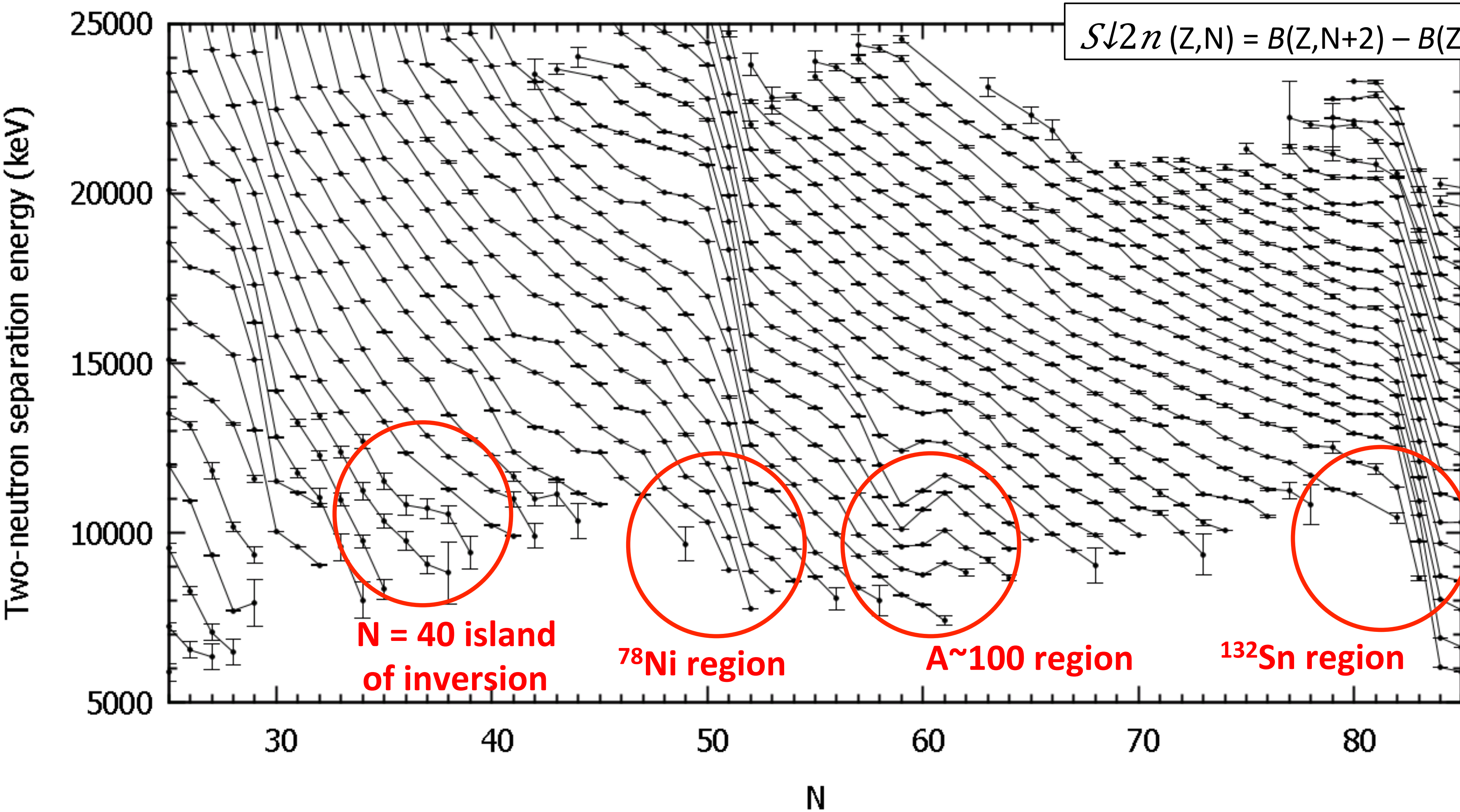


- Ions of different masses mutually perturb their resonance frequency $\nu_+ + \nu_- \neq \nu_c$

Results

Results

S_{2n} (Z,N) = B(Z,N+2) – B(Z, N



M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

Results

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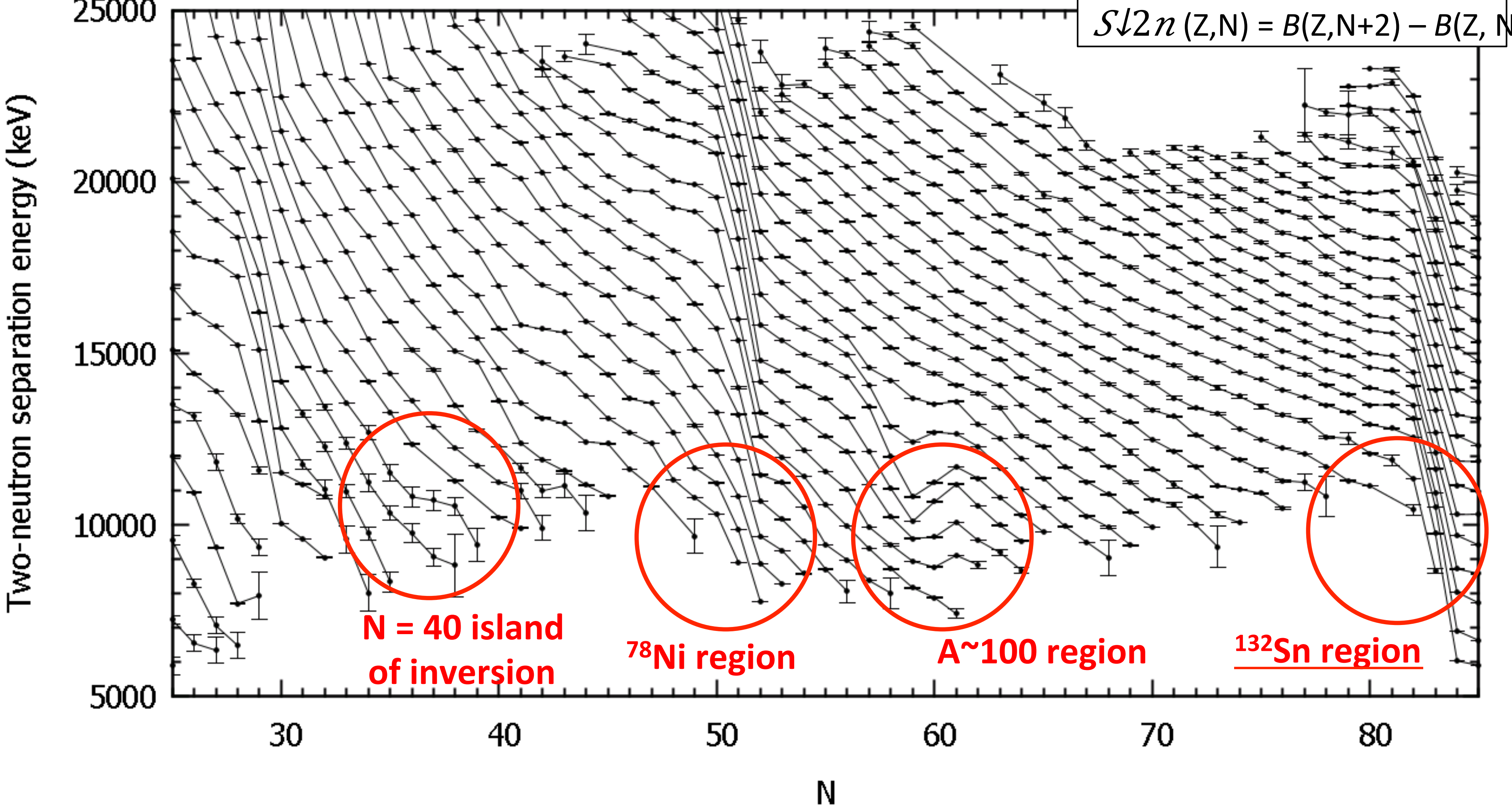
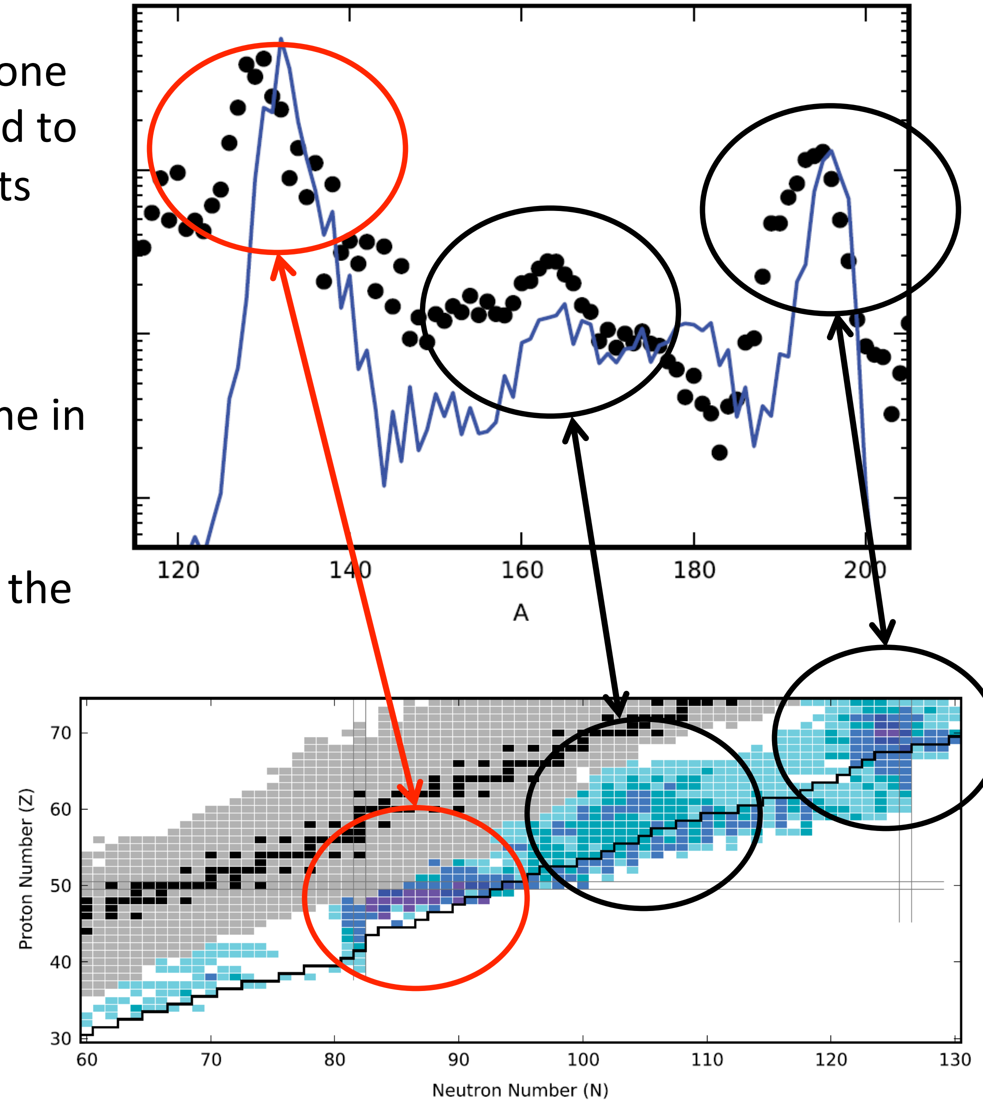


M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

Neutron-rich cadmium isotopes

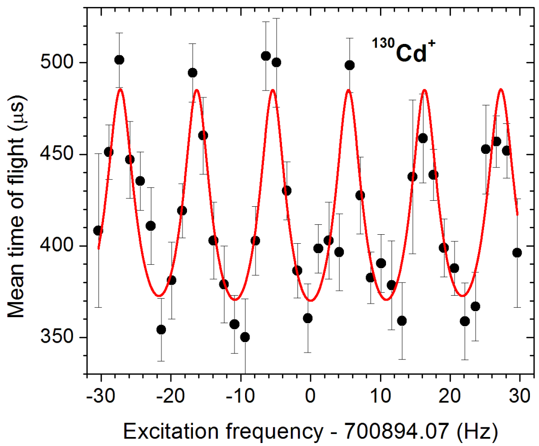
- The **rapid neutron-capture process** is one of the important mechanisms proposed to explain the nucleosynthesis of elements heavier than iron.
- **Atomic masses** are a crucial input for r-process simulations.
- The masses of $^{>129}$**Cd** isotopes intervene in the description of the A = 130 peak of isotopic abundance.
- $^{128\text{-}132}$**Cd** masses reveal the strength of the N = 82 magic number below Z = 50.

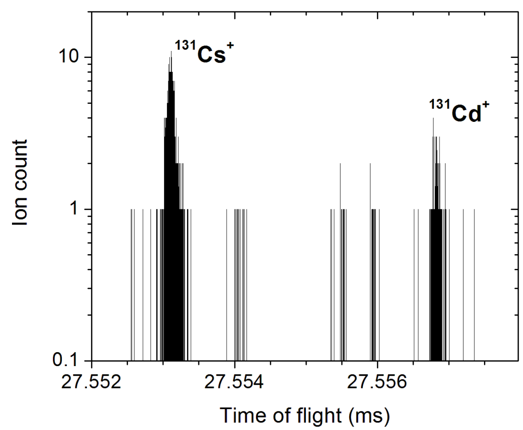


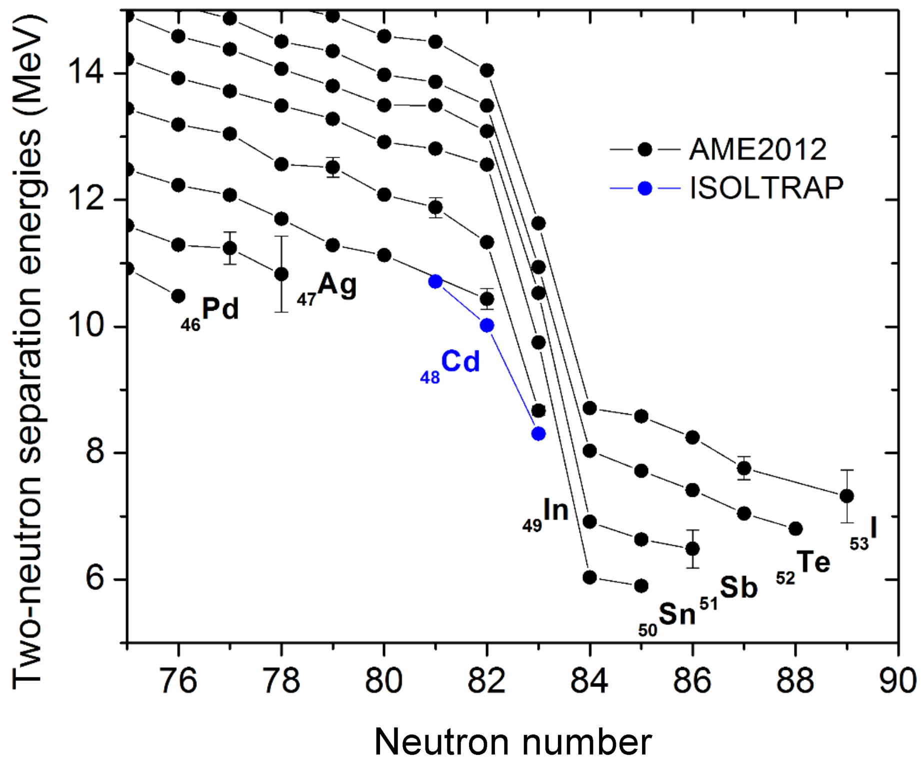
M. Arnould, S. Goriely, and K. Takahashi, Phys. Rep. **450**, 97 (2007).
M. R. Mumpower *et al.*, Progr. Part. Nucl. Phys. **86**, 86-126(2016).

Mass measurements of $^{129\text{-}131}$Cd

- N-rich cadmium beams from UC_x with neutron converter and cold quartz line.
- Masses of $^{129\text{-}130}$Cd were determined with the precision Penning trap, of ^{131}Cd with the MR-TOF MS.



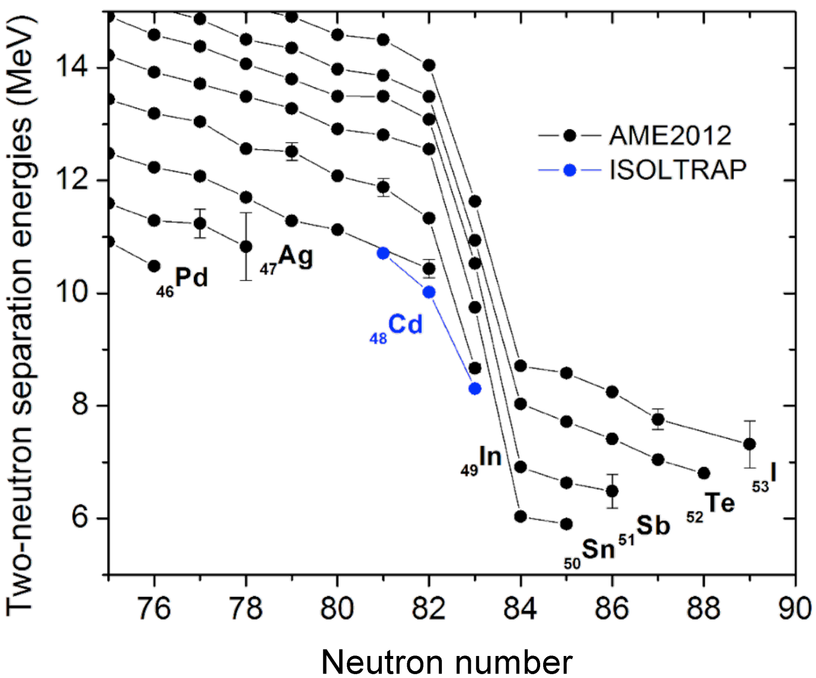


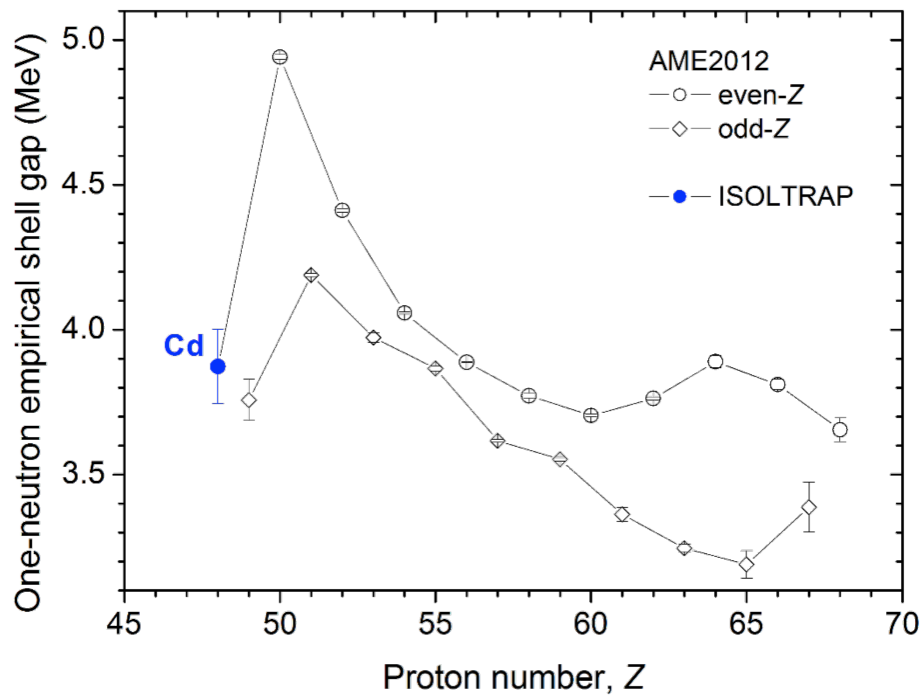


M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).

Mass measurements of $^{129-131}$Cd

- Because we are missing the mass of ^{132}Cd, we can only compute the one-neutron shell gap.



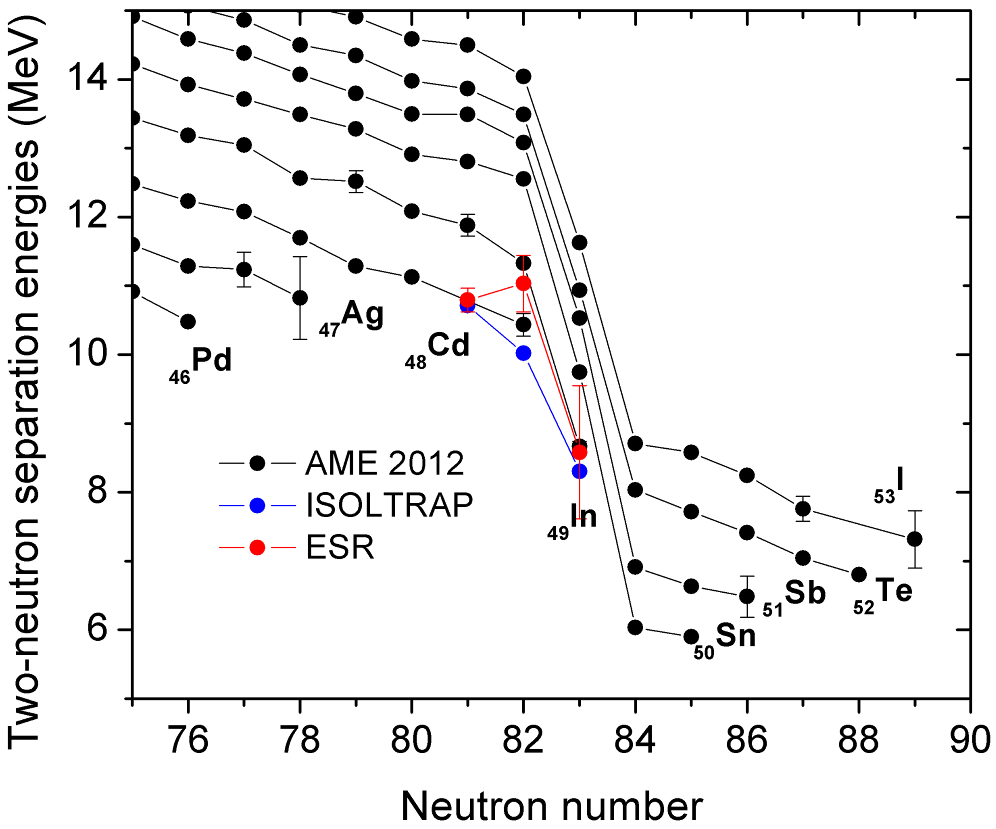


$$D_{n}(Z,N) = 2B(Z,N) - B(Z, N-1) - B(Z,N+1)$$

M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).

Mass measurements of $^{129-131}Cd$

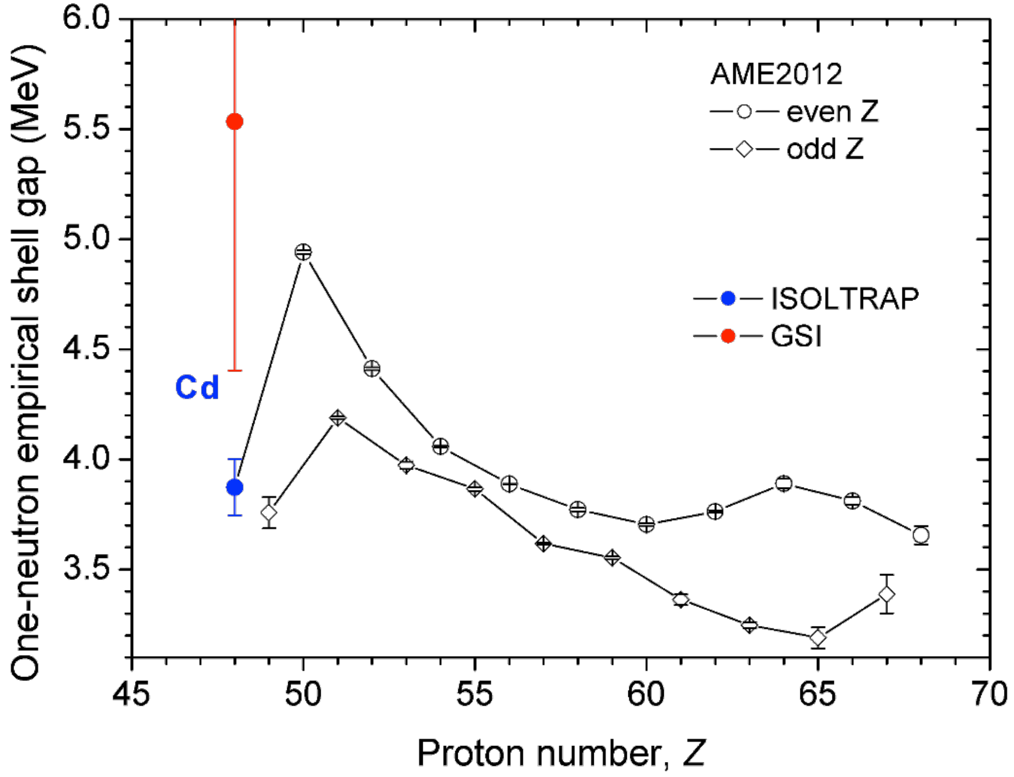
- Disagreement with the masses measured by ESR at GSI.



M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).
R. Knöbel et al., Phys. Lett. B **754**, 288–293 (2016).

Mass measurements of $^{129\text{-}131}$Cd

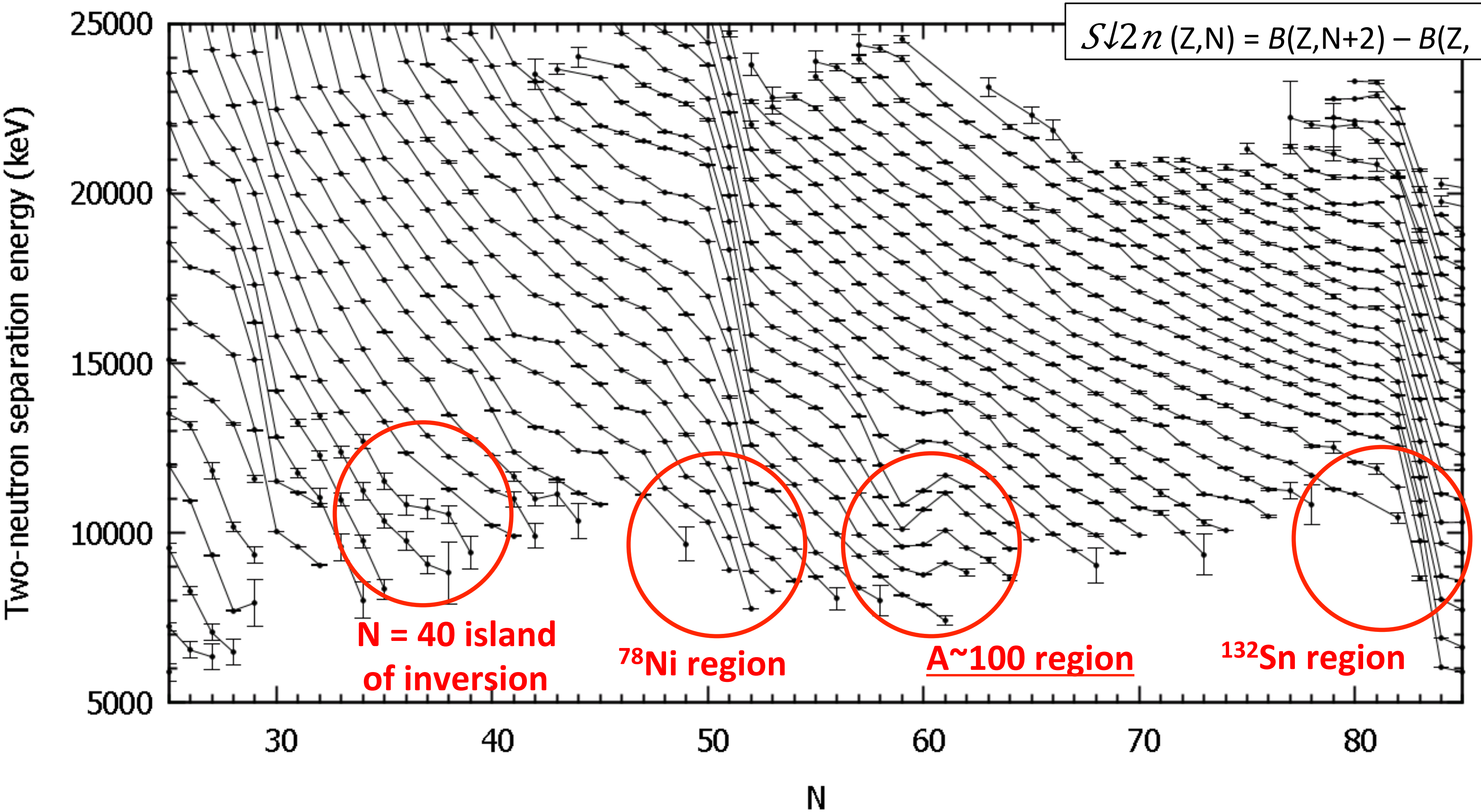
- Disagreement with the masses measured by ESR at GSI.



$$D_n(Z,N) = 2B(Z,N) - B(Z, N\text{-}1) - B(Z,N\text{+}1)$$

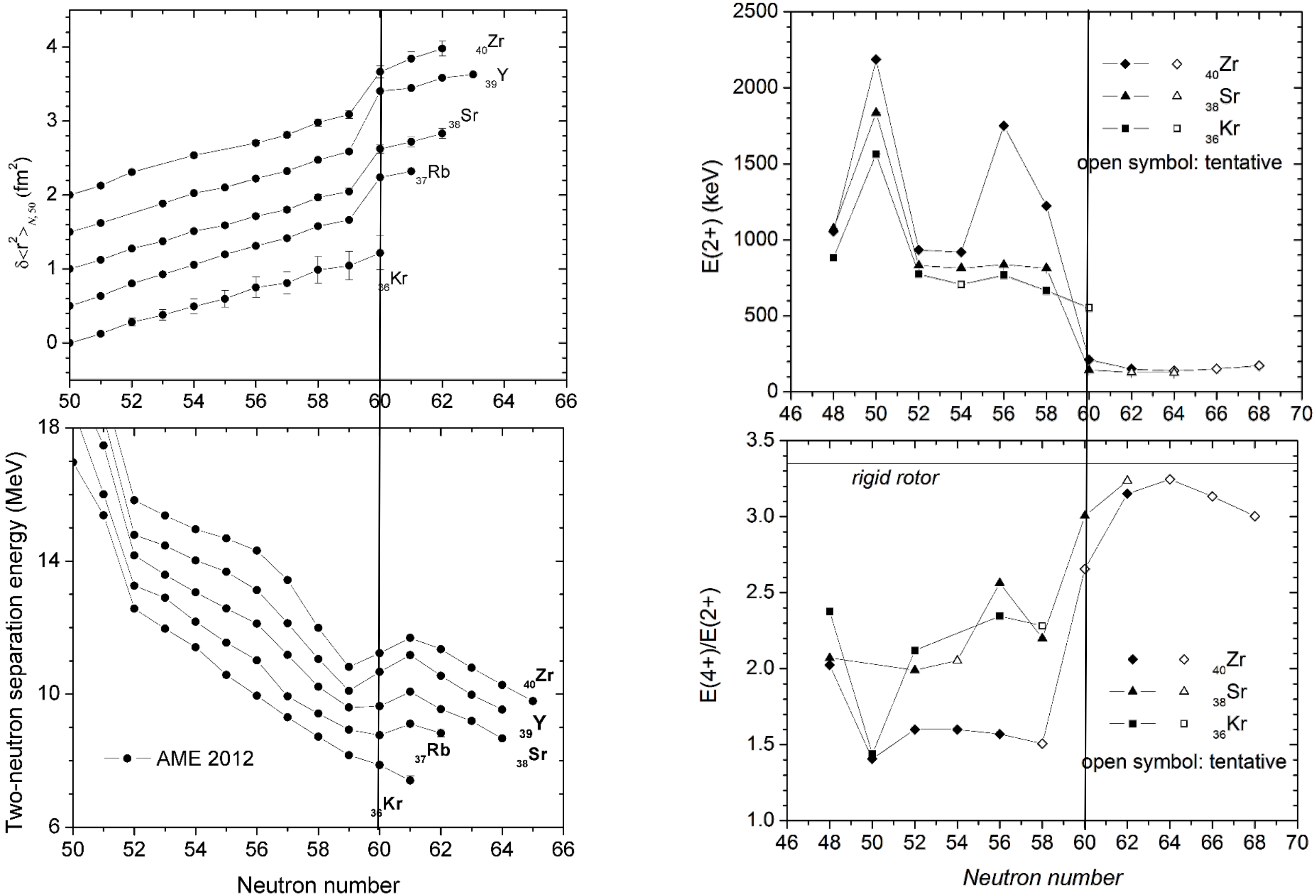
M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).
R. Knöbel et al., Phys. Lett. B **754**, 288–293 (2016).

Results



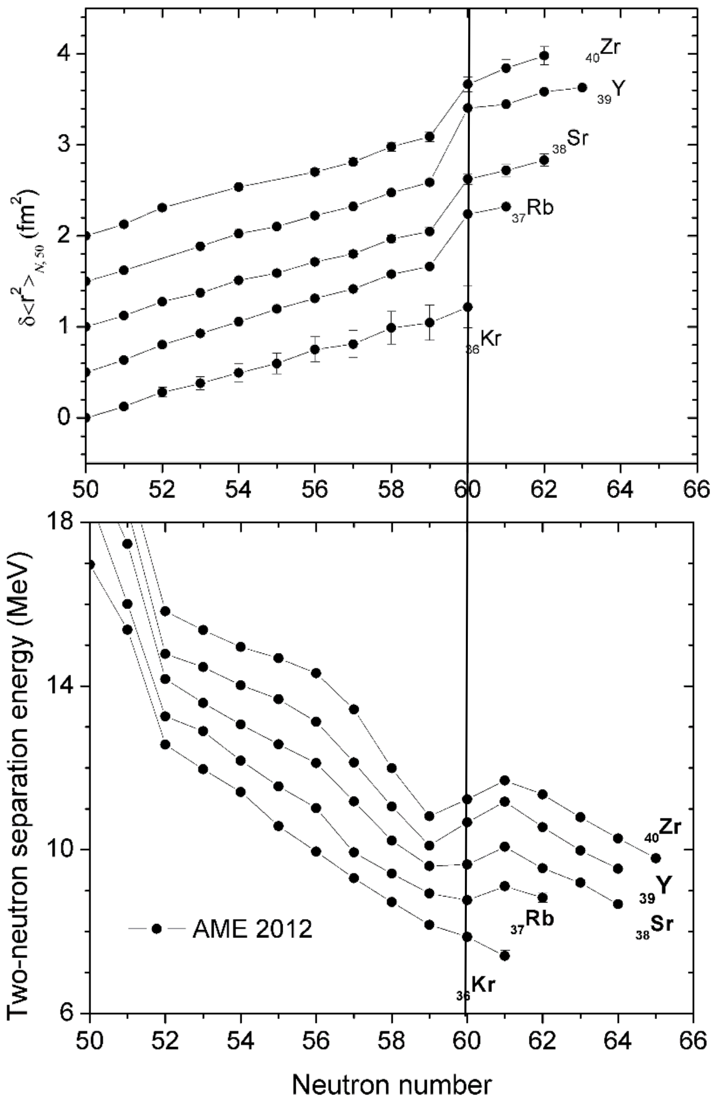
M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

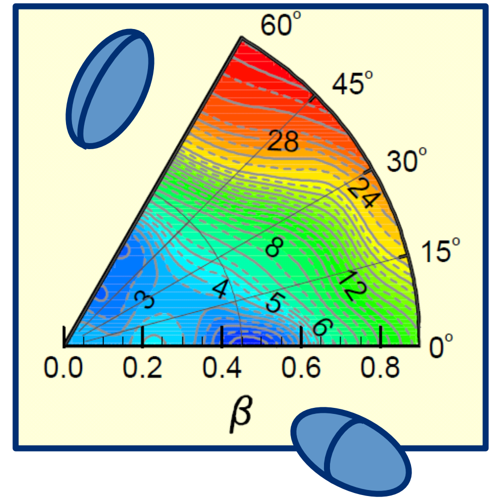
A ≈ 100 nuclides: onset of collectivity at *N* = 60

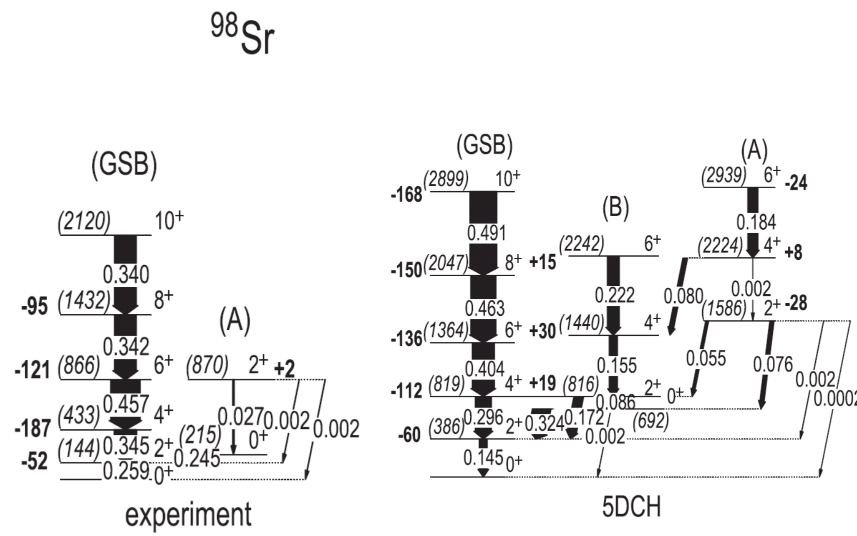


Masses: M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
Radii: Keim95; Thibault81; Buchinger90; Lievens91; Cheal07; Campbell97; Campbell02; Thayer03.
Excitation energies: ENSDF 2016;

$A \approx 100$ nuclides: onset of collectivity at $N = 60$



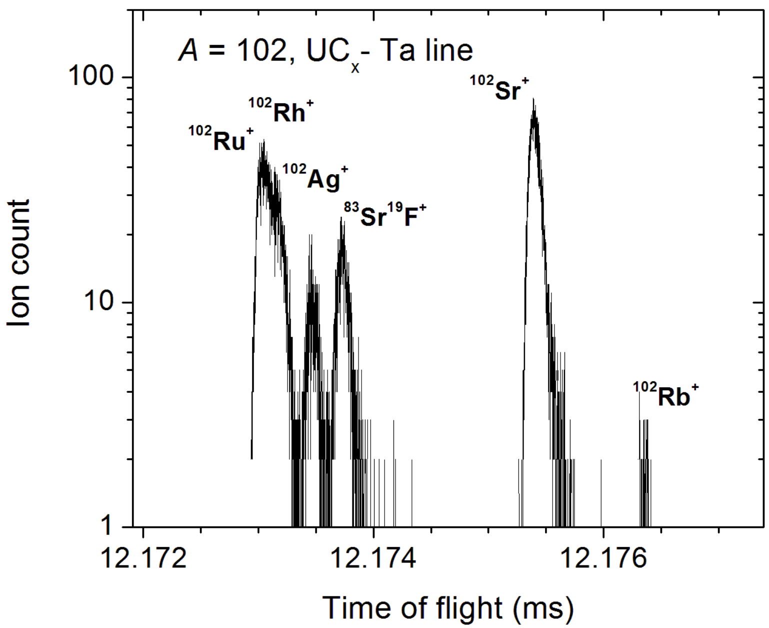


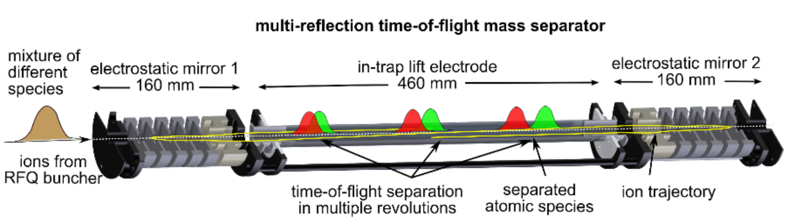


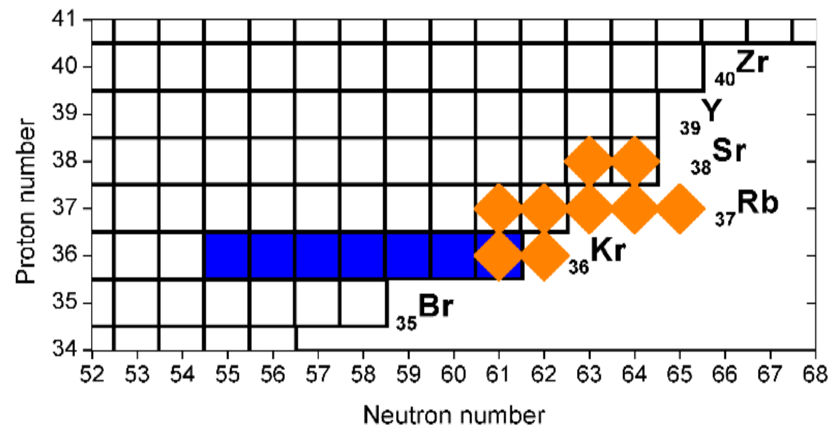
Gogny-D1S calculations: J. P. Delaroche *et al.*, Phys. Rev. C **81**, 014303 (2010).
^{98}Sr scheme: E. Clément *et al.*, Phys. Rev. Lett. **116**, 022701 (2016).

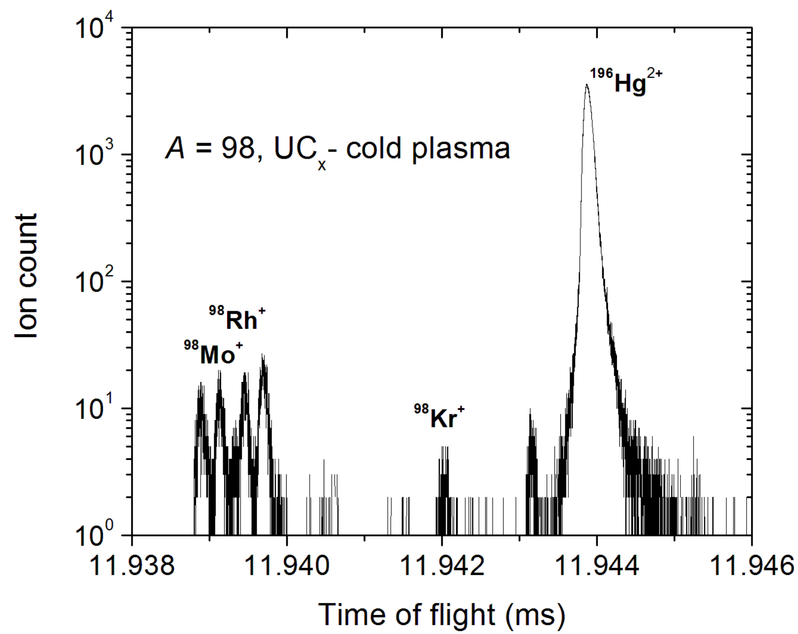
Masses of neutron-rich nuclides in the A ≈ 100 region

- Three campaigns in the $A \approx 100$ region during the last four years.
- ^{101,102}Sr, $^{98\text{-}100}$Rb, ^{97}Kr measured with Penning trap, $^{100\text{-}102}$Rb, ^{98}Kr with MR-TOF MS.



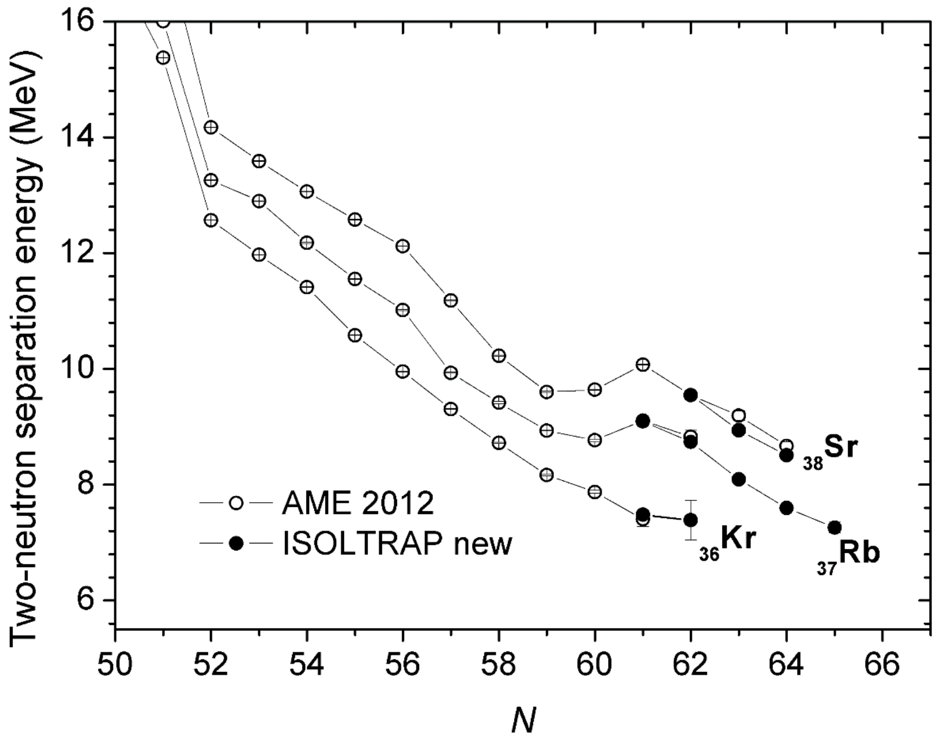


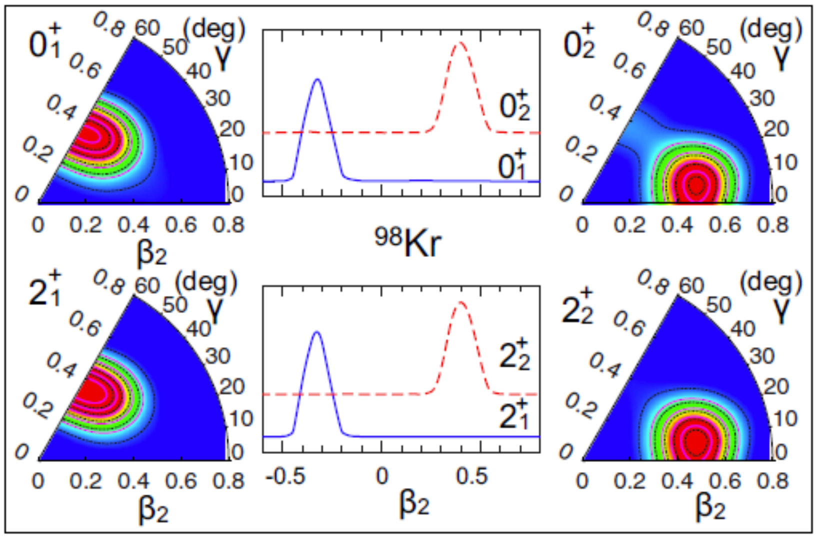




S. Naimi *et al.*, Phys. Rev. Lett. **105**, 032502 (2010).
P. Delahaye *et al.*, Phys. Rev. C **74**, 034331 (2006).
V. Manea *et al.*, Phys. Rev. C **88**, 054322 (2013).
A. de Roubin, article and thesis in preparation.

Two-neutron separation energies around A ≈ 100

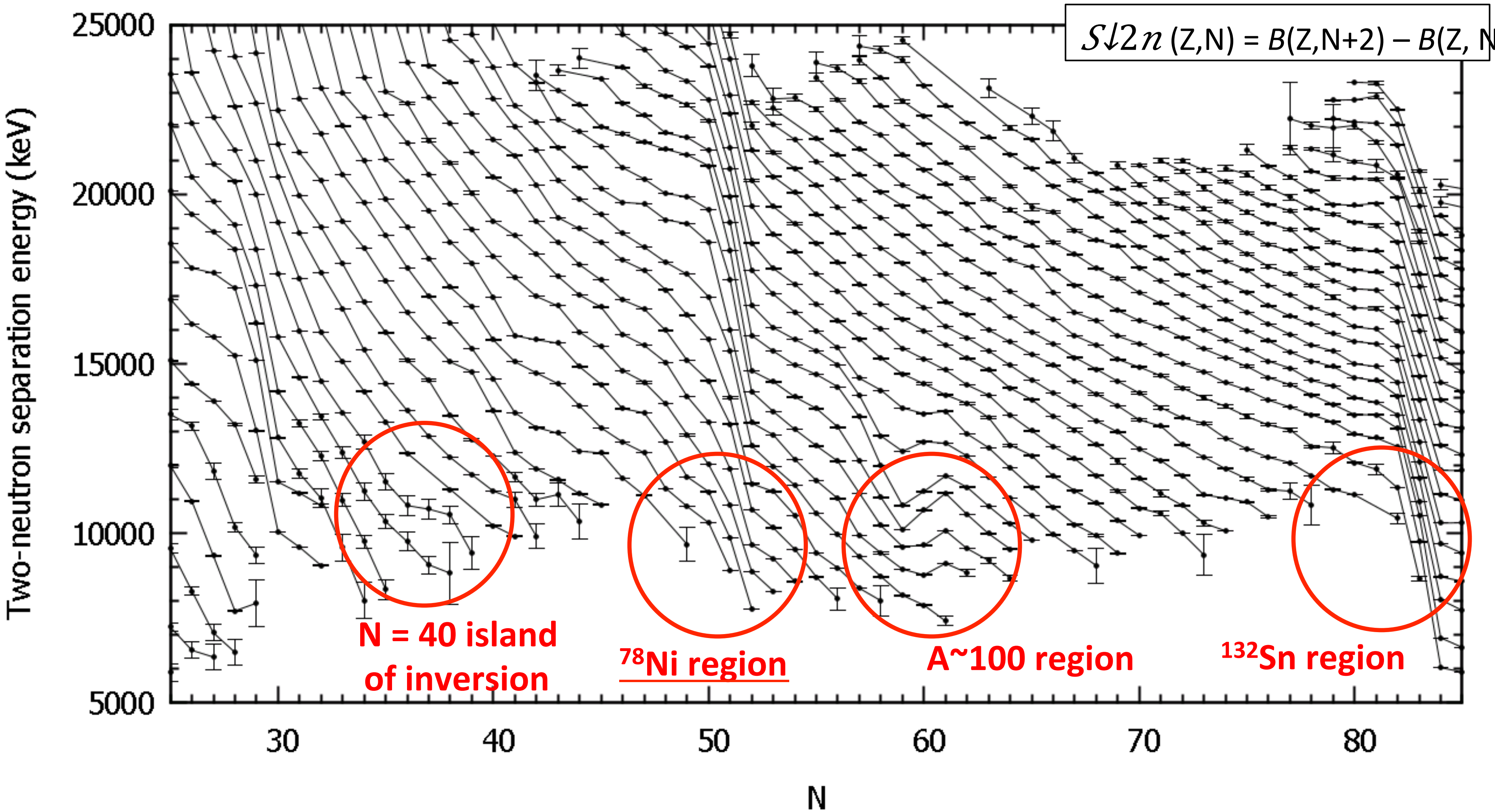




- New ISOLTRAP data continue the previous trends in the Sr and Rb chains. More precise measurements in the Kr chain are needed.
- Beyond-mean-field calculations show that the Kr configurations don't mix strongly in the ground state.

M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
V. Manea, PhD thesis (2014).
A. de Roubin, article and thesis.
TITAN: R. Klawitter et al., Phys. Rev. C 93, 045807 (2016).
T. R. Rodriguez, Phys. Rev. C **90**, 034306 (2014)

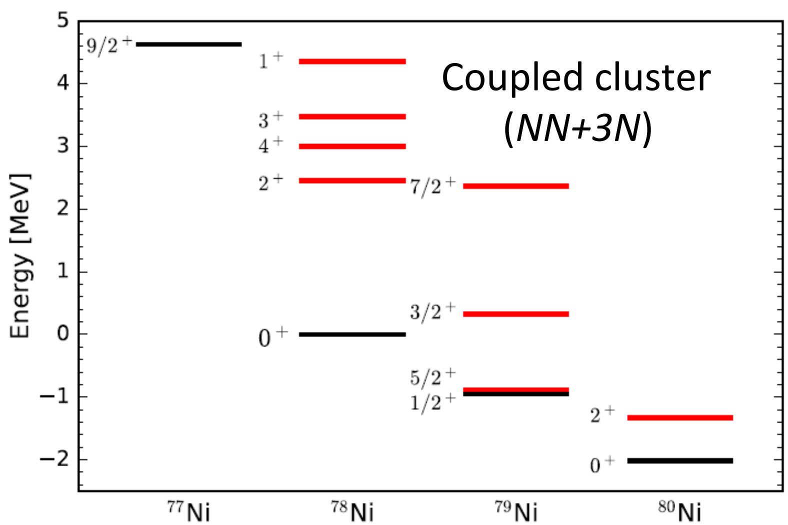
Results

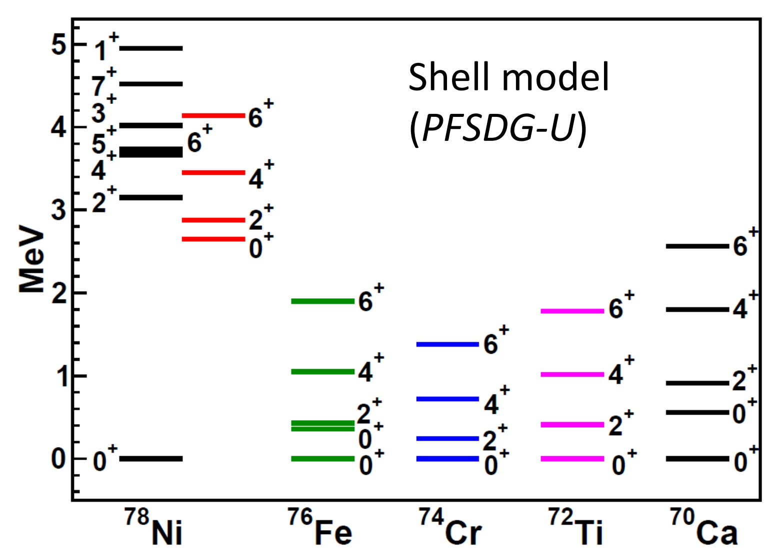


M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

Mass measurements of $^{75-79}Cu$

- ^{78}Ni region is (re-)becoming a hot topic with the emergence of new data and new calculations.
- The expectation is that **^{78}Ni is doubly-magic** but that shell-model requires **cross-shell excitations** (proton and neutron) to describe the properties of neighbouring nuclides.

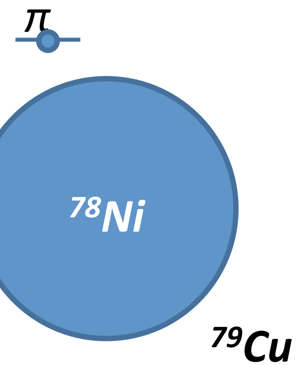




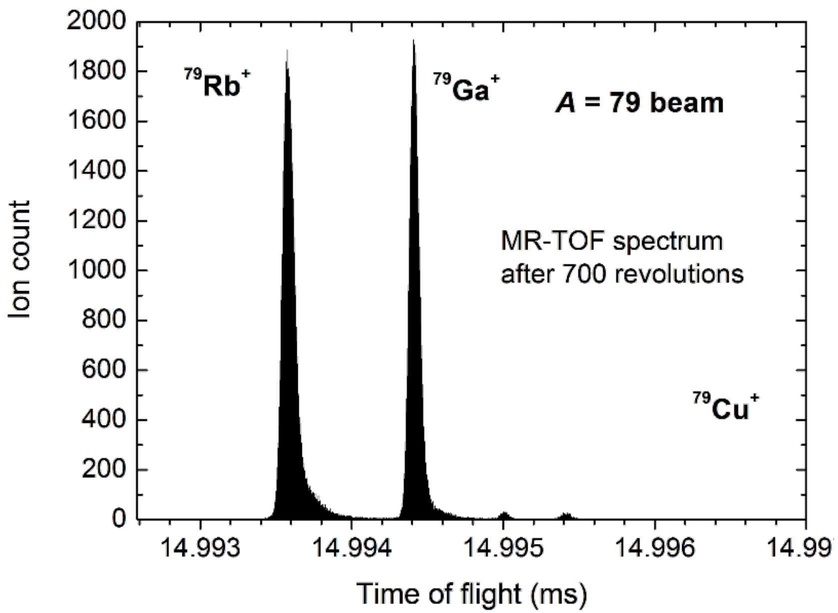
G. Hagen, G. R. Jansen, T. Papenbrock et al., Phys. Rev. Lett. 117, 172501 (2016).
F. Nowacki, A. Poves, E. Caurier, B. Bounthong, Phys. Rev. Lett. 117, 272501 (2016).
A. Welker *et al.*, paper in preparation.

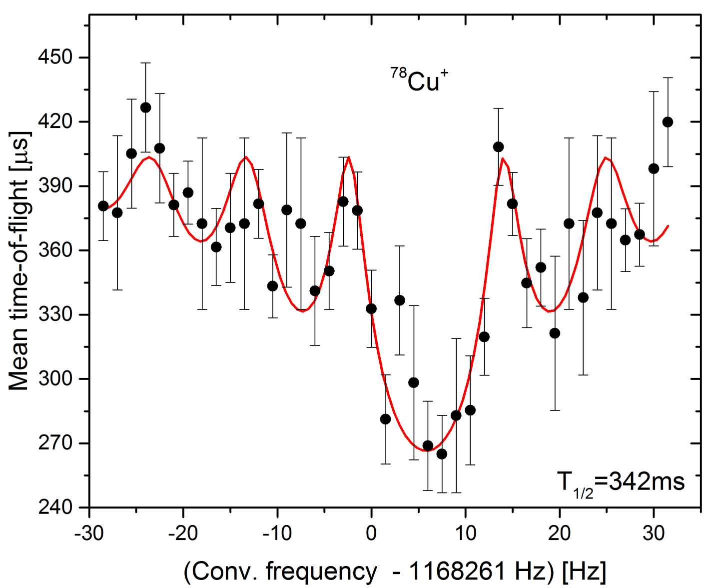
Mass measurements of $^{75-79}Cu$

- N-rich copper beams produced from UC_x with neutron converter.
- Masses of $^{75-78}Cu$ were determined with the precision Penning trap, of $^{78,79}Cu$ with the MR-TOF MS.



Highly contaminated by Rb and Ga
Rate of less than 10 ions/s.





Mass measurements of $^{75\text{-}79}Cu$

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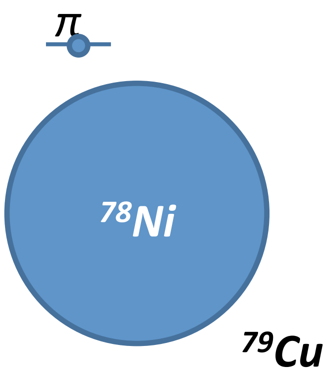
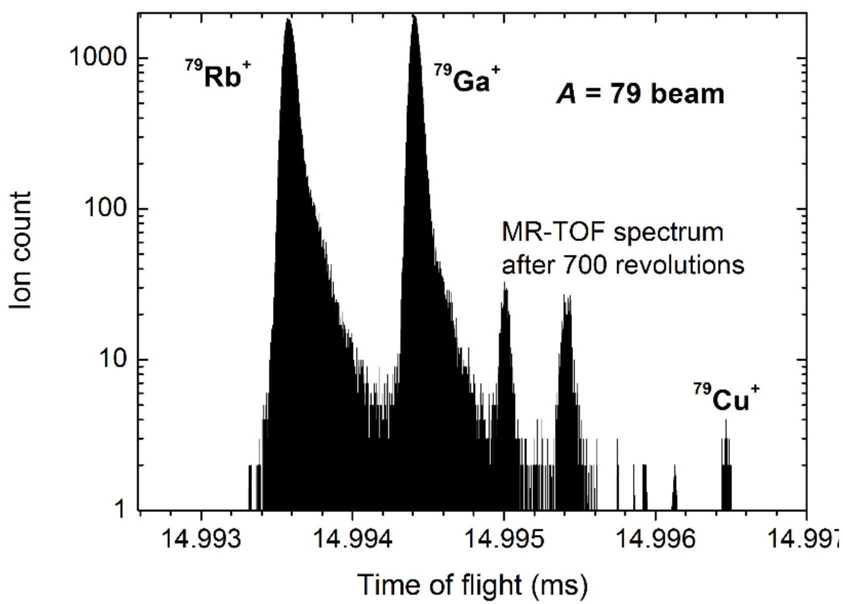
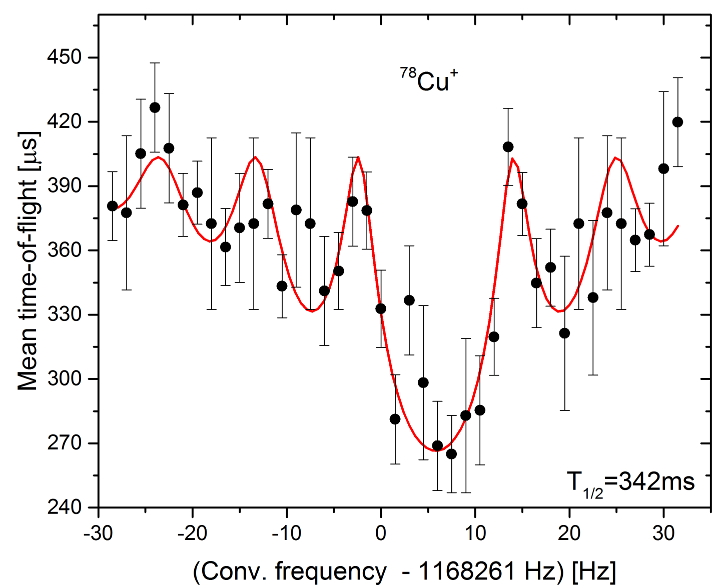
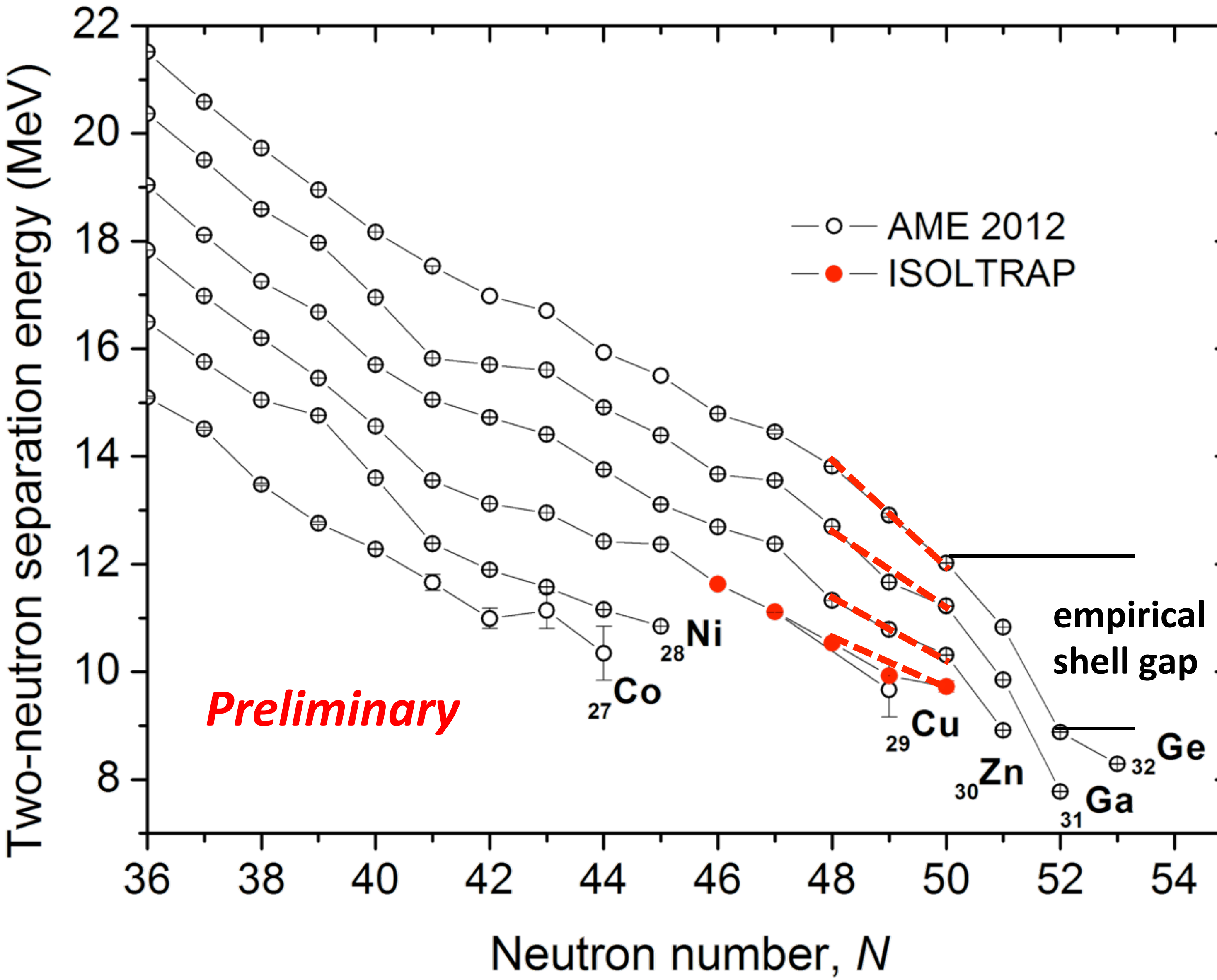
Rate of less than 10 ions/s.







What can't and what can we tell?

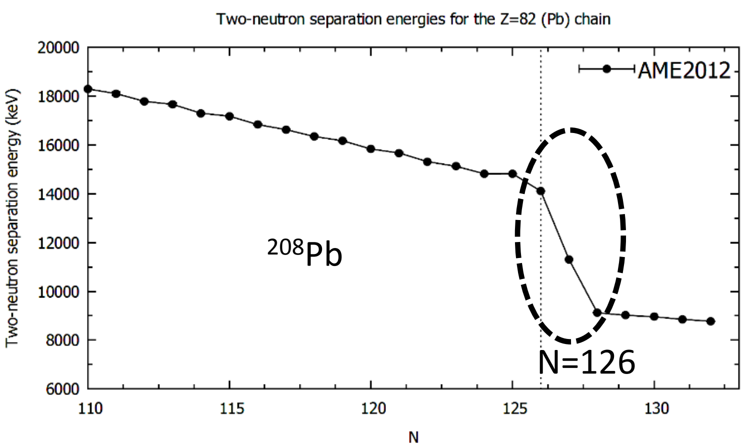


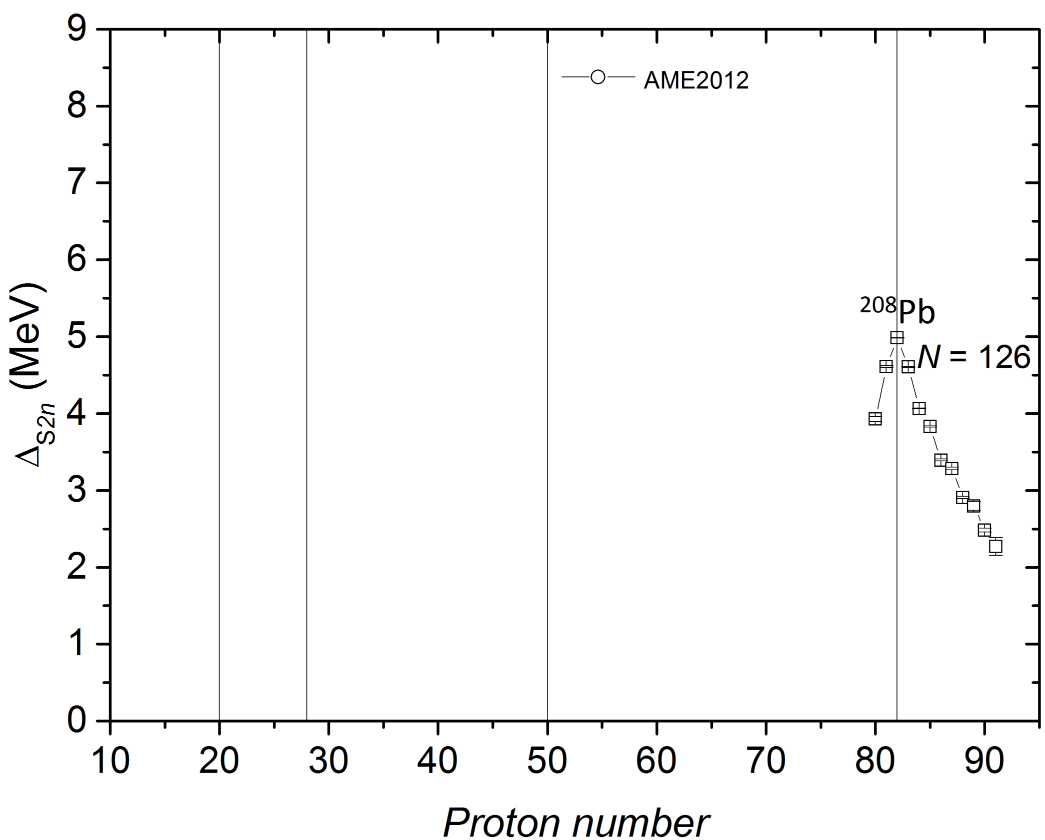
A. Welker *et al.*, paper in preparation.
M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

Neutron-rich copper isotopes

➢ Analysis of doubly-enhanced magicity across the nuclear chart.

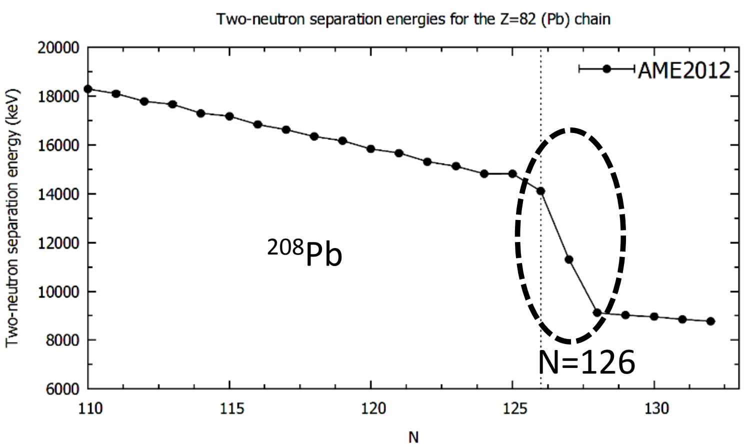
$\Delta_{S2n}(Z, N_0)$ (black)



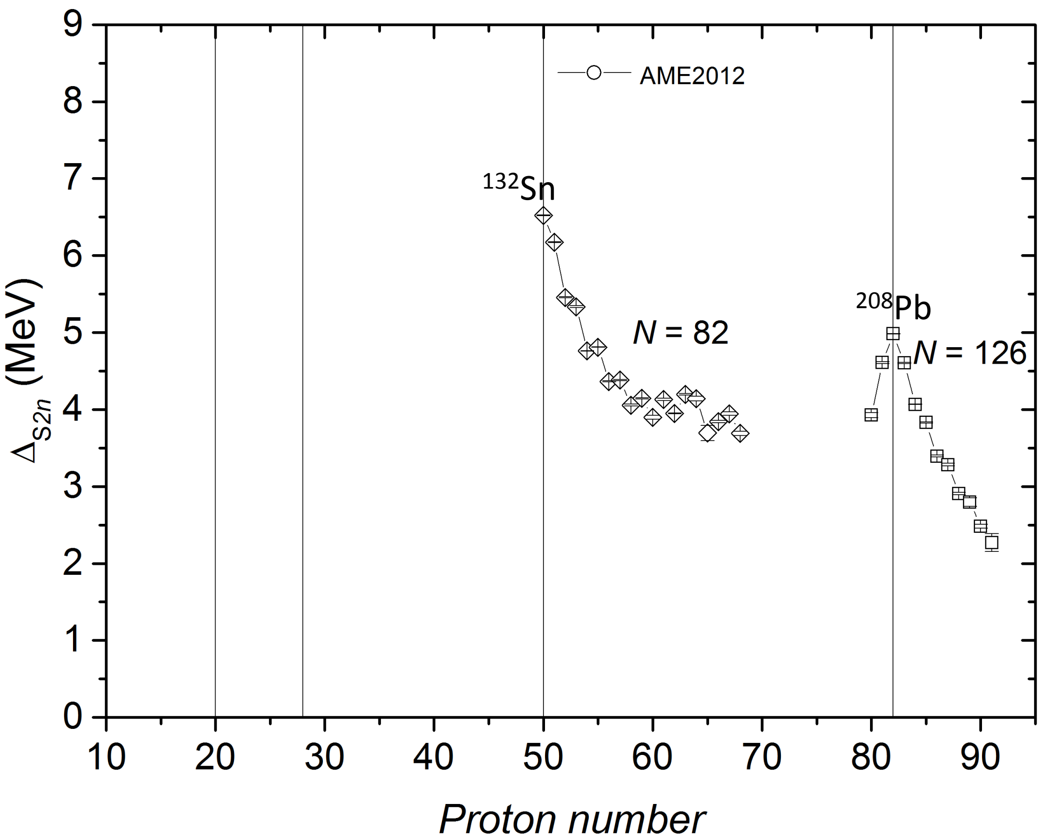


Neutron-rich copper isotopes

- Analysis of doubly-enhanced magicity across the nuclear chart.



$\Delta_{S2n}(Z, N_0)$ (black)



Neutron-rich copper isotopes

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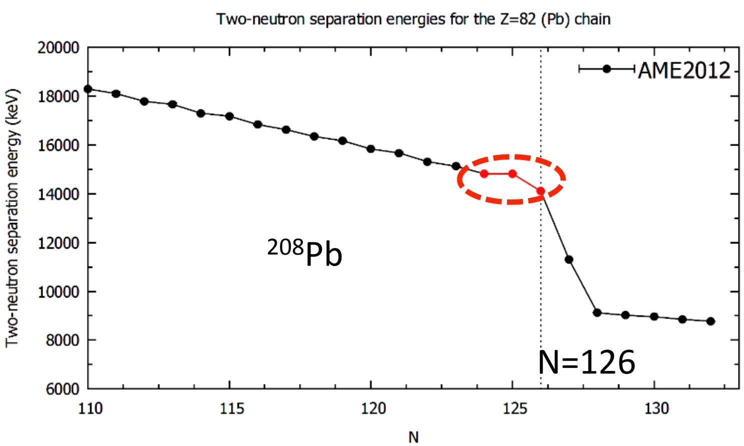
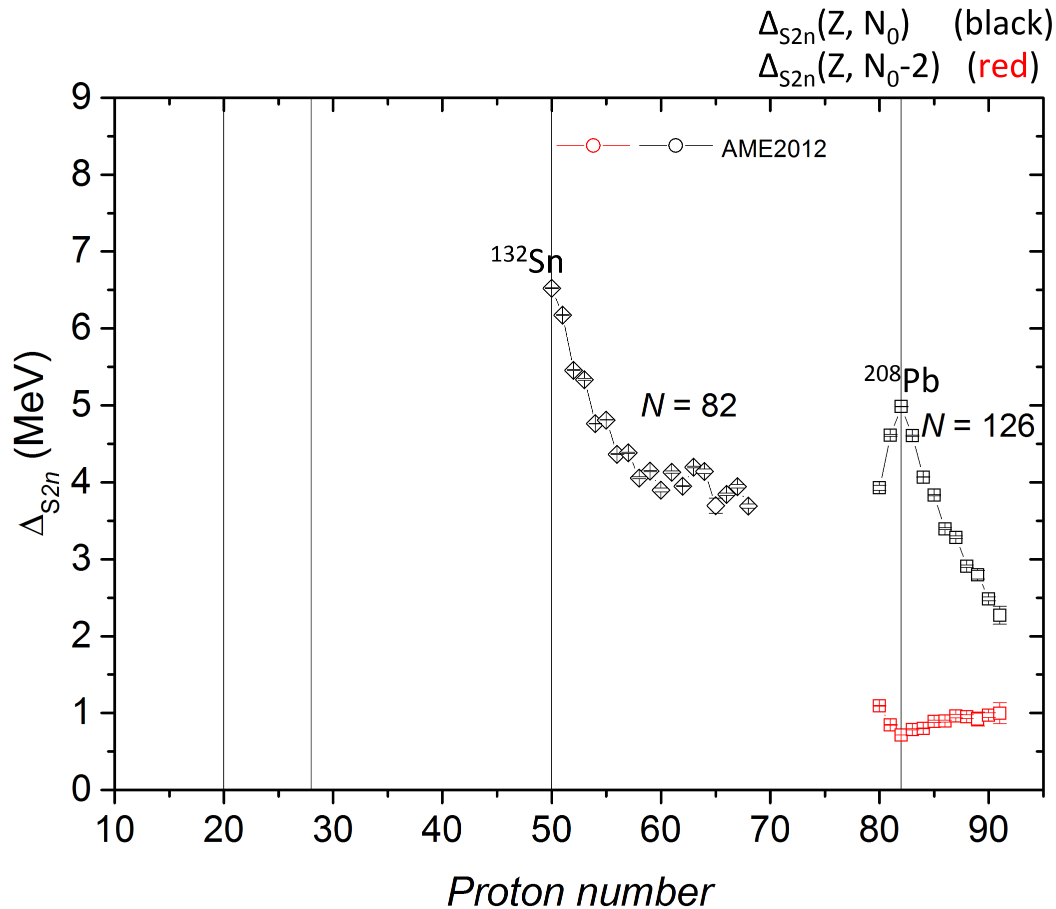
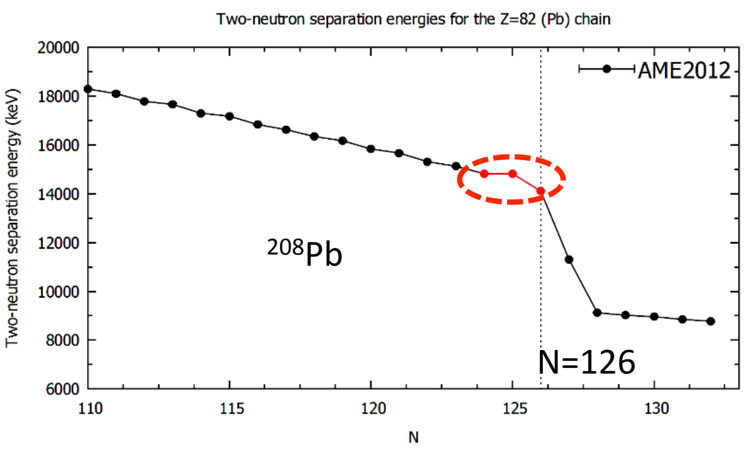
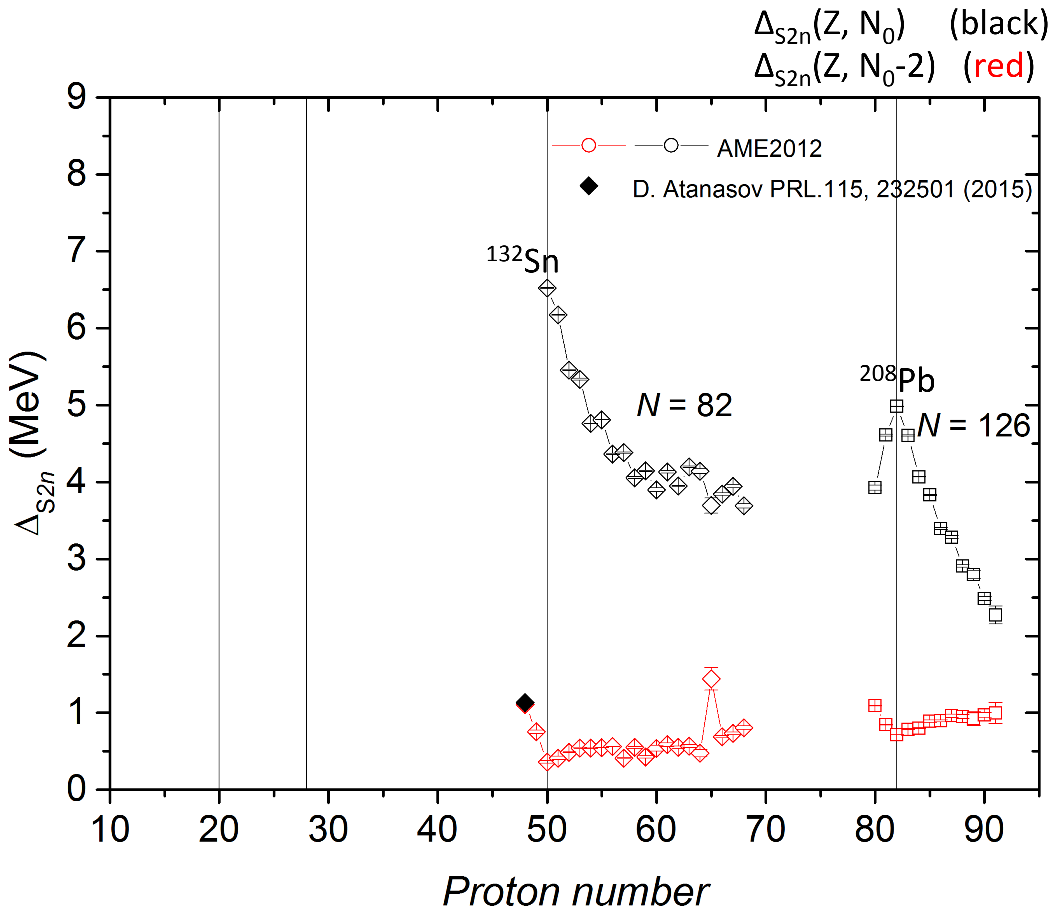




Neutron-rich copper isotopes

➢ Analysis of doubly-enhanced magicity across the nuclear chart.





Neutron-rich copper isotopes

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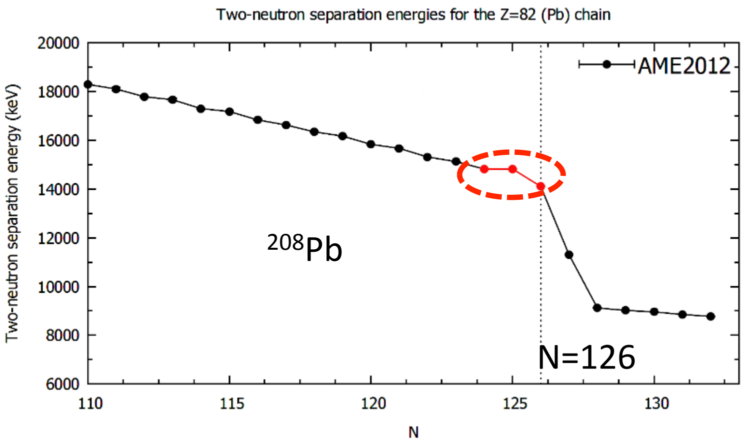
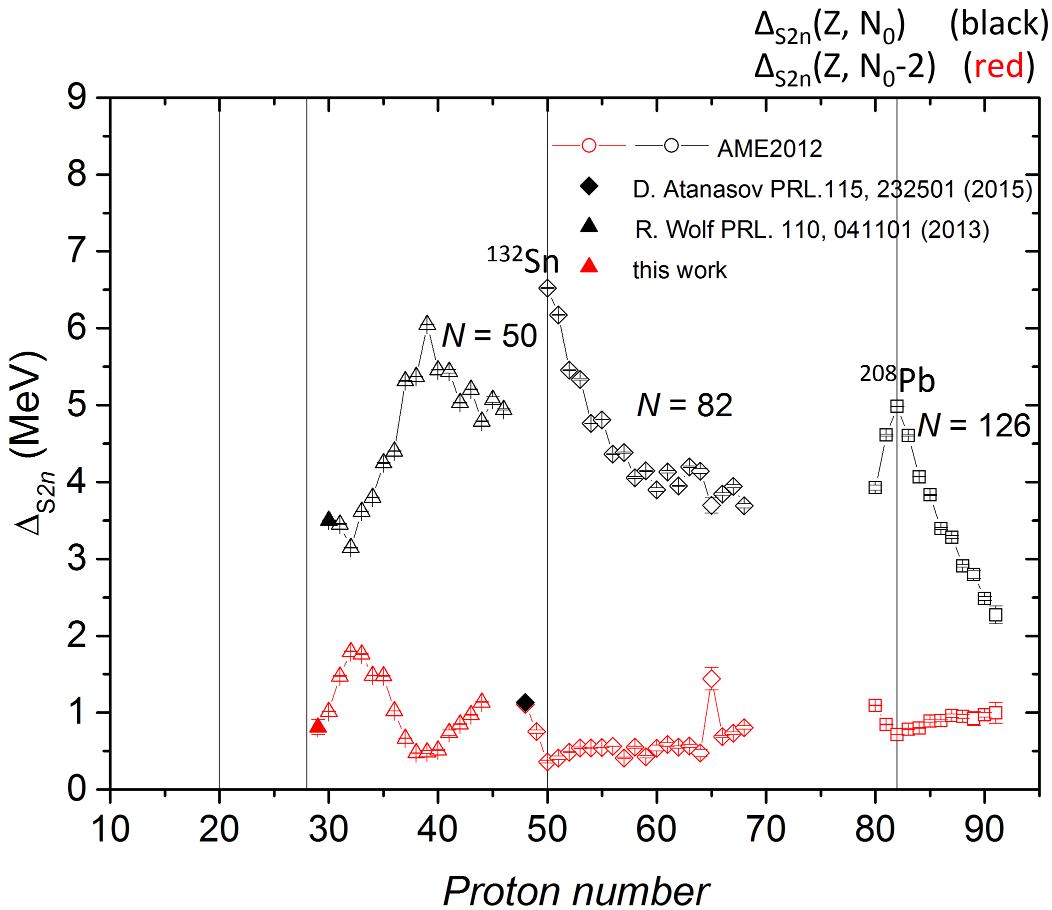
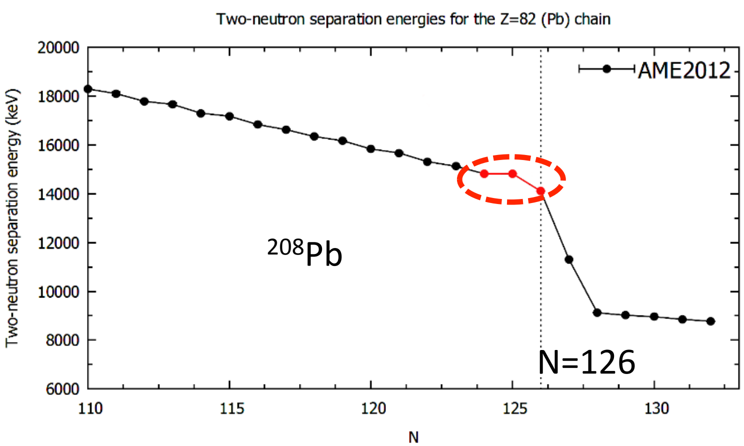
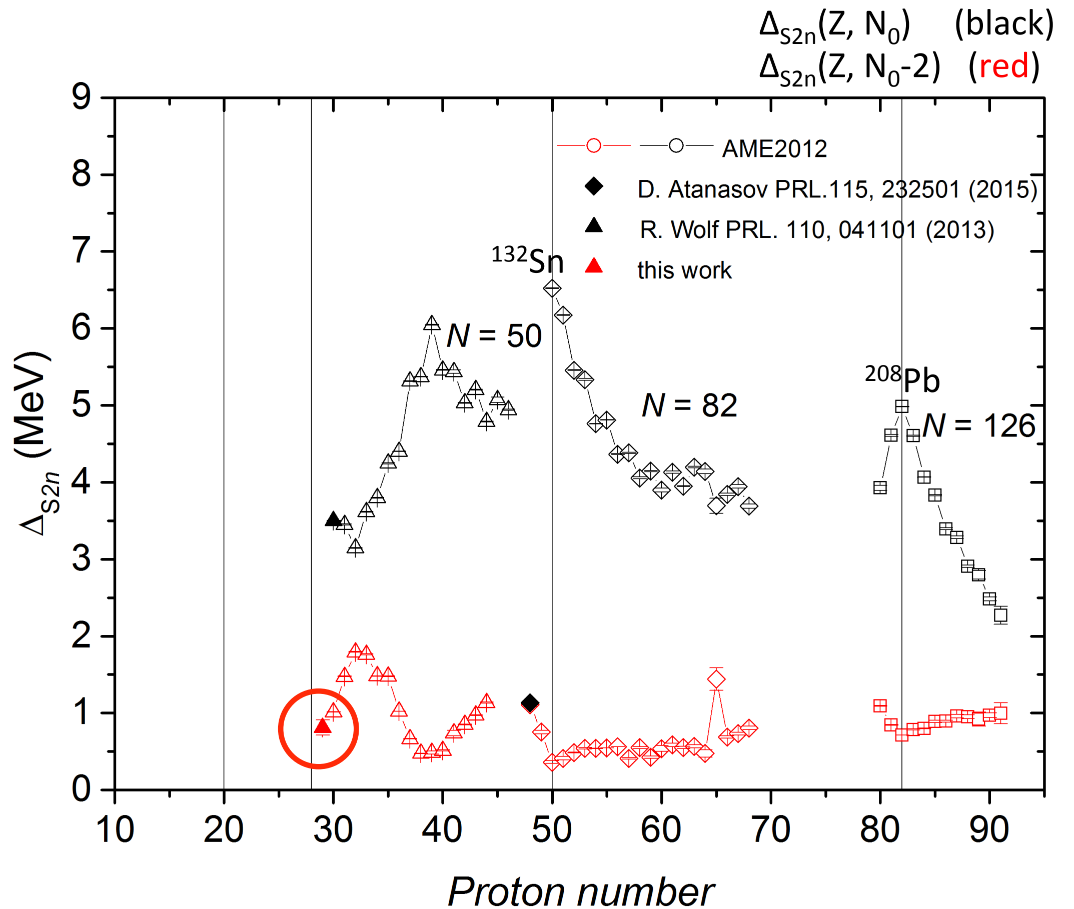




Neutron-rich copper isotopes

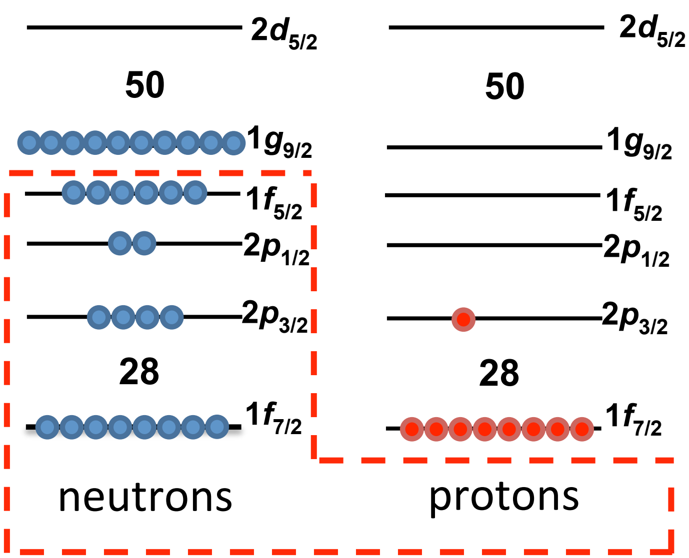
- Analysis of doubly-enhanced magicity across the nuclear chart.
- The trend of S_{2N} in the copper chain before N = 50 behaves as if we are approaching a doubly-magic ^{78}Ni.

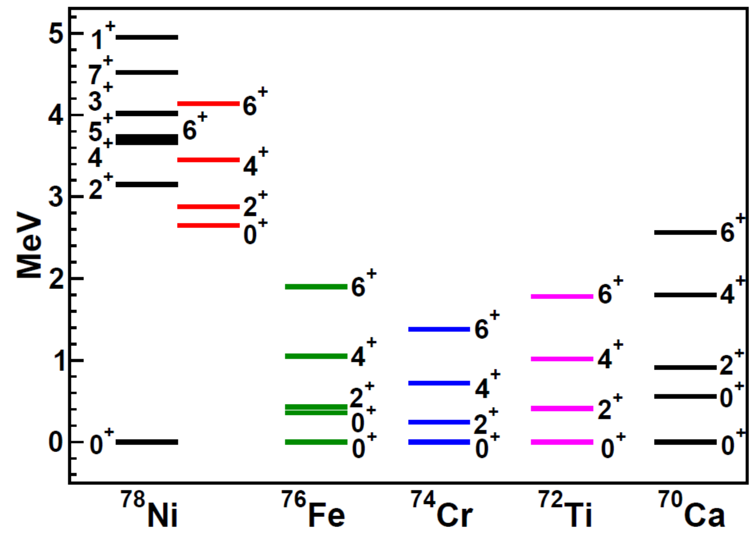


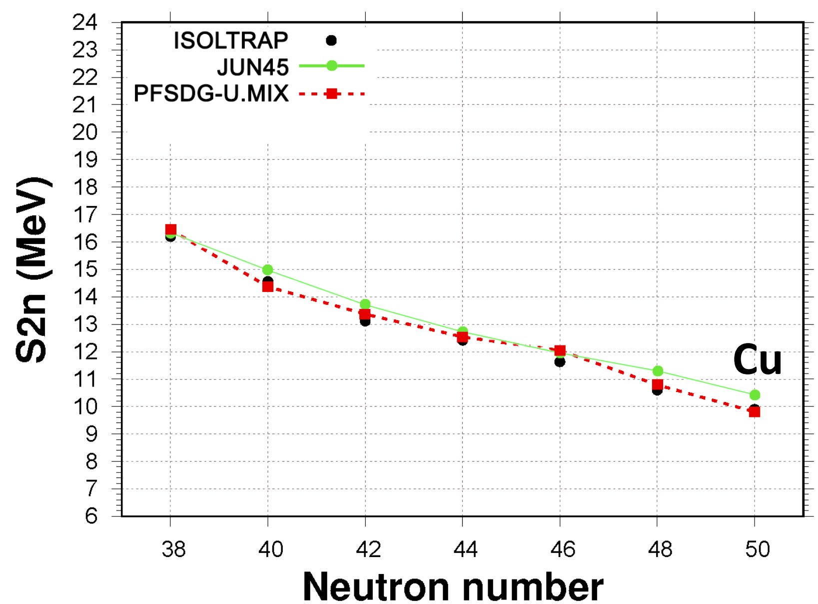


Neutron-rich copper isotopes

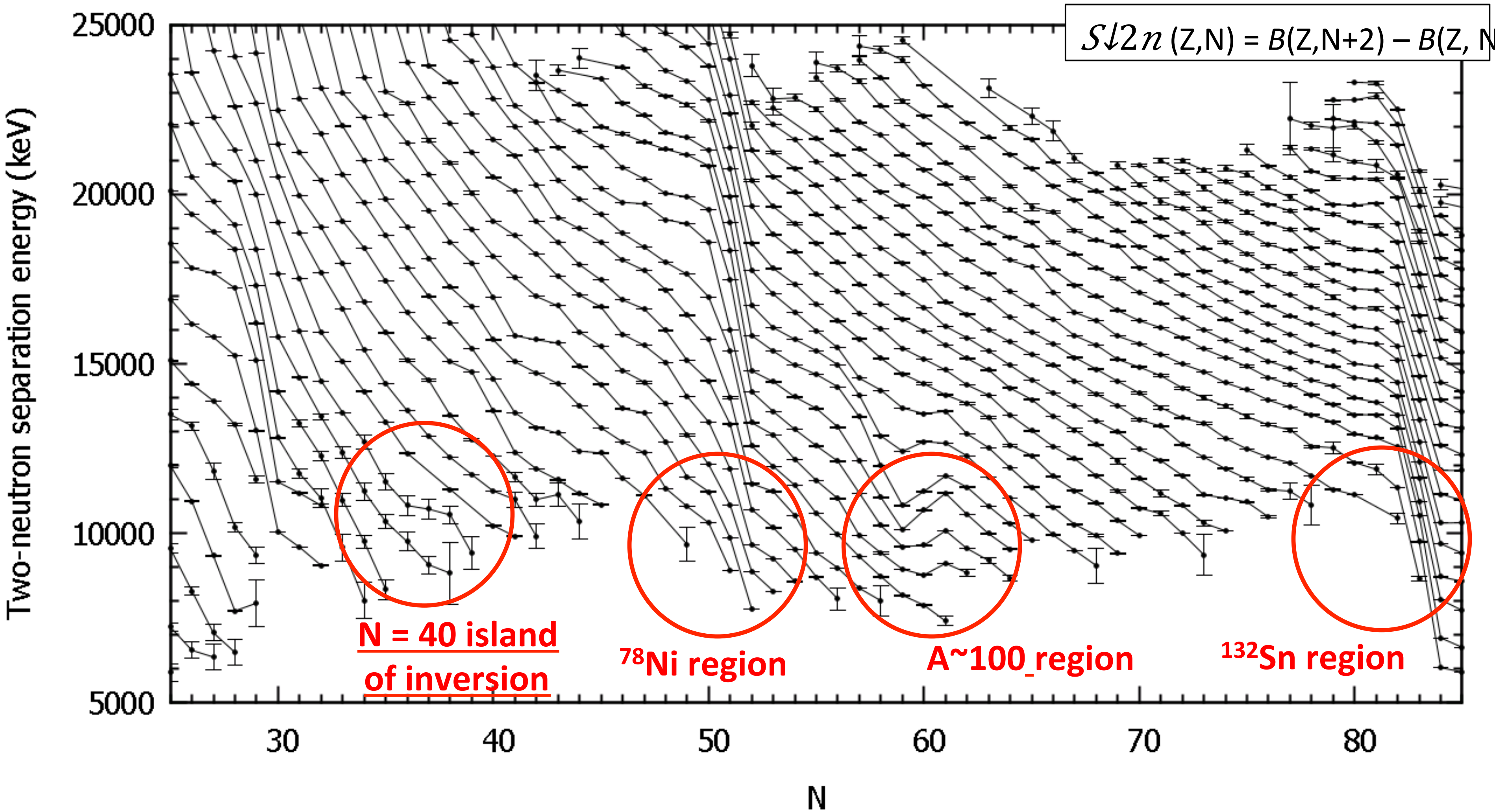
- PFSDG allows excitations across Z =28 and N = 50.
- Improve description of S_{2N} values and observe the impact on the predicted properties of ^{78}Ni.







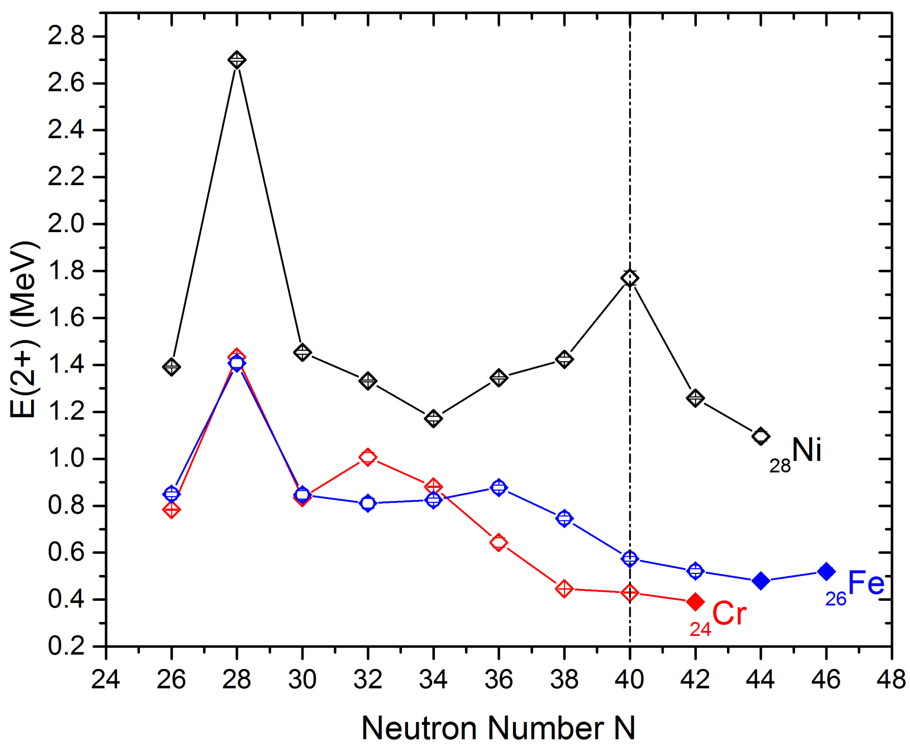
Results

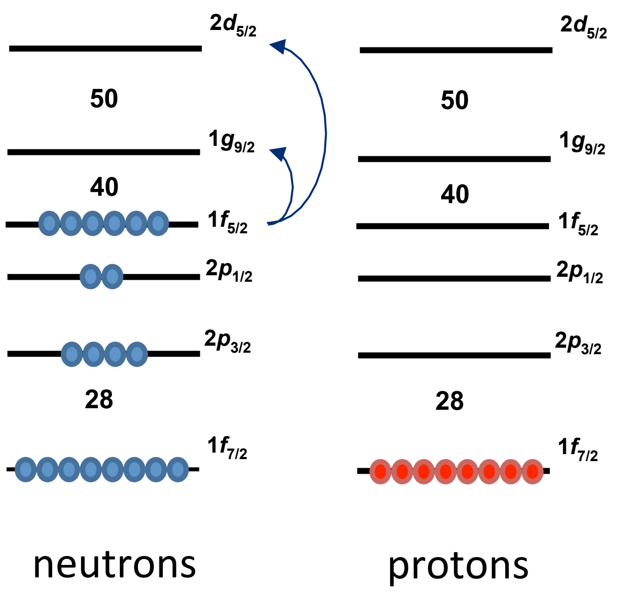


M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

The N = 40 island of inversion

- Quick evolution from doubly-magic like ^{68}Ni to deformed-like ^{64}Cr.

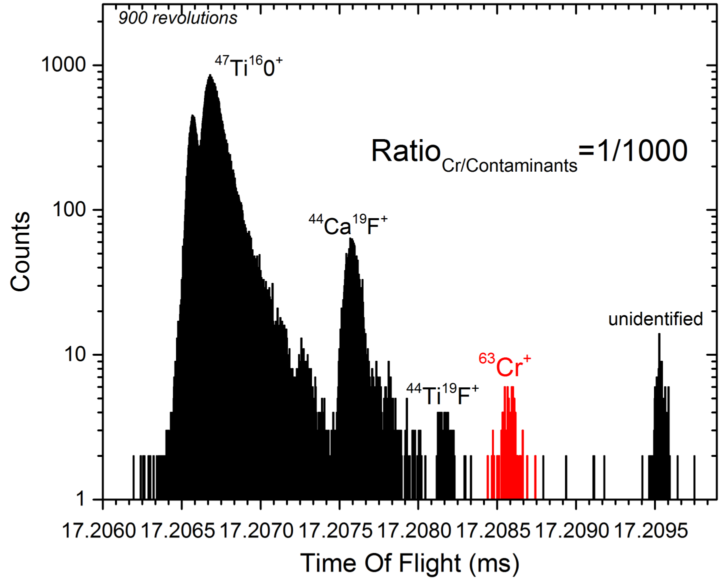


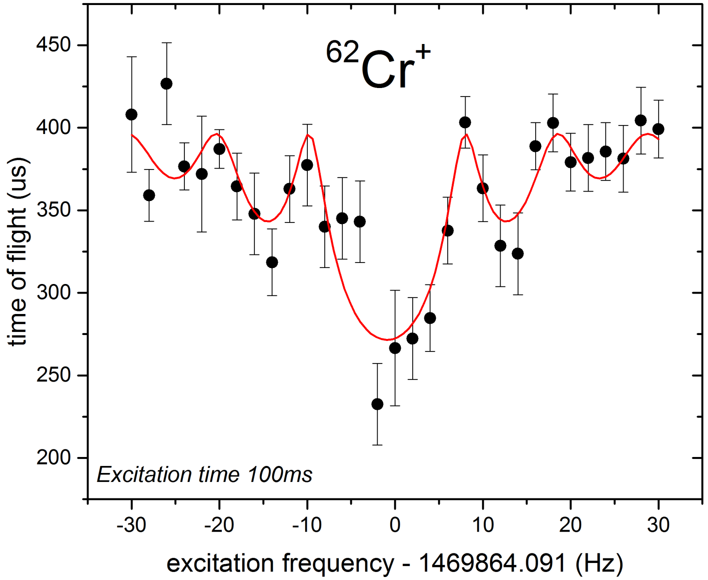


S. M. Lenzi *et al.*, Phys. Rev. C **82**, 054301 (2010).
ENSDF database (2015).
C. Santamaria *et al.*,PRL **115**, 192501 (2015).

Neutron-rich chromium isotopes

Isotope	Measured with	Half life (ms)	Yield (ions/s)
^{59}Cr	Penning Trap/MR-TOF	1050	3E5
^{60}Cr	Penning Trap/MR-TOF	490	2E4
^{61}Cr	Penning Trap/MR-TOF	243	2E3
^{62}Cr	Penning Trap/MR-TOF	206	3E2
^{63}Cr	MR-TOF	129	30

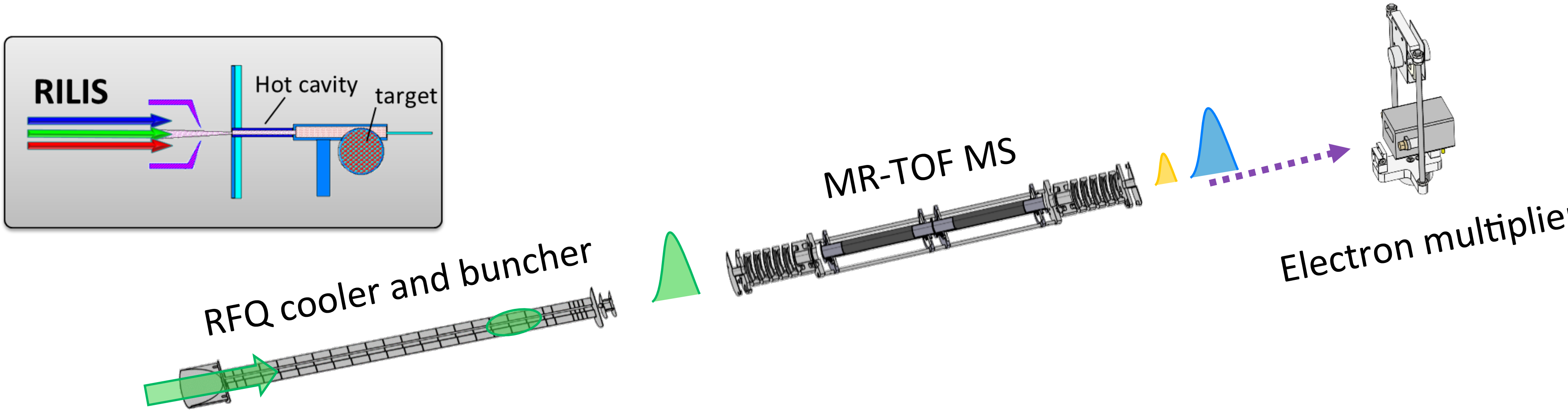




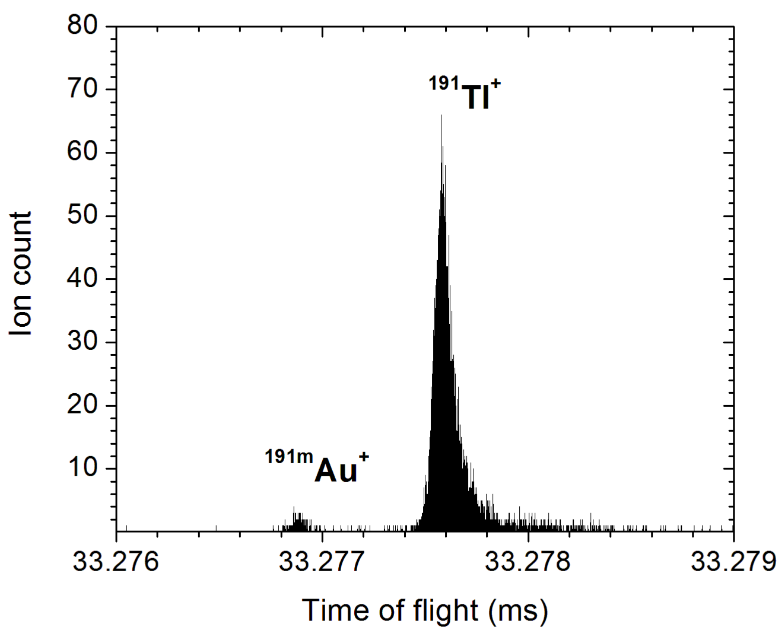
M. Mougeot et al., paper in preparation.
T.D Goodacre *et al.,* Spectrochimica Acta B (in press).

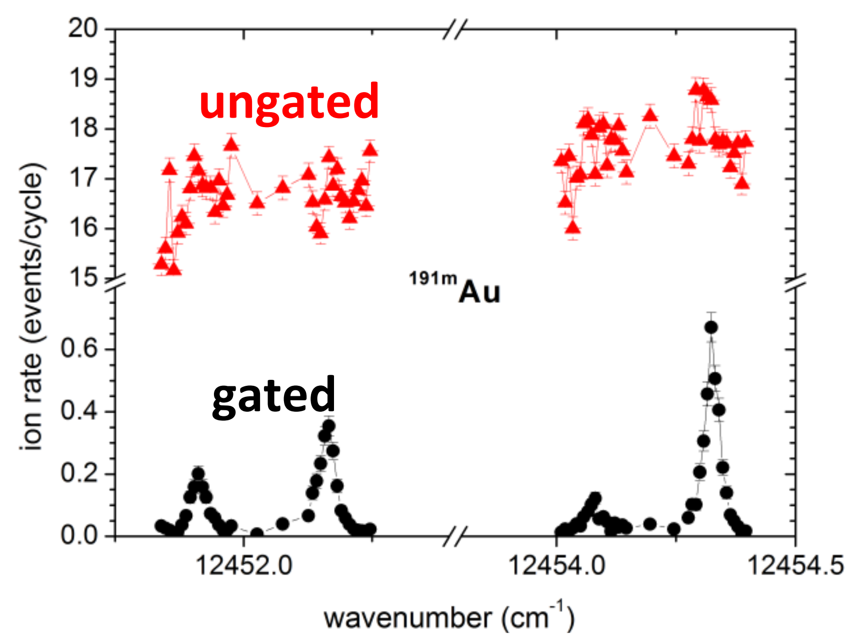
Perspectives

HFS studies in the neutron-deficient lead region

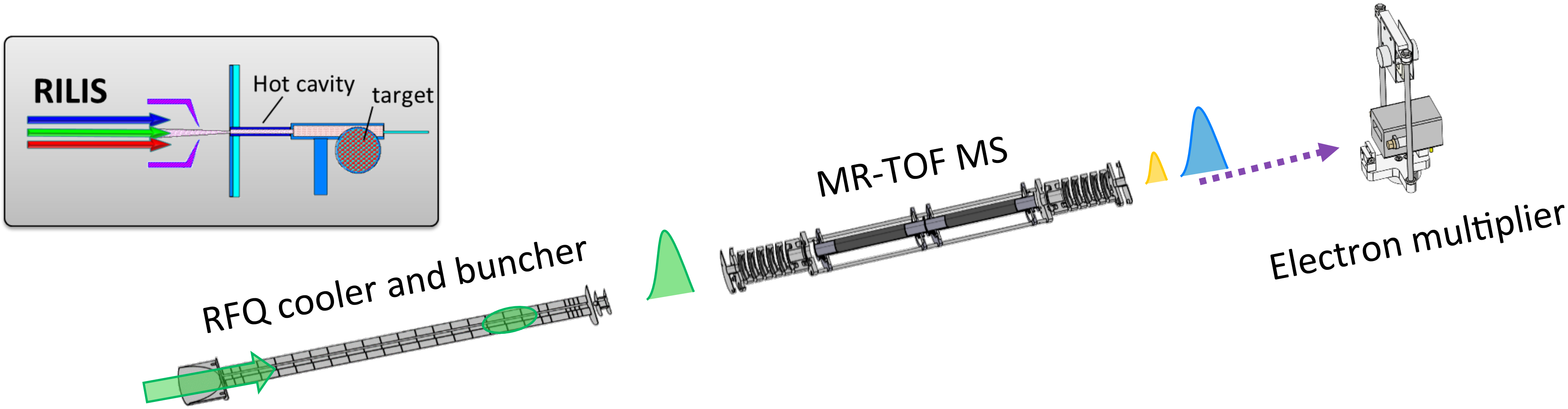


Direct ion detection: no decay mode/half-life limit.

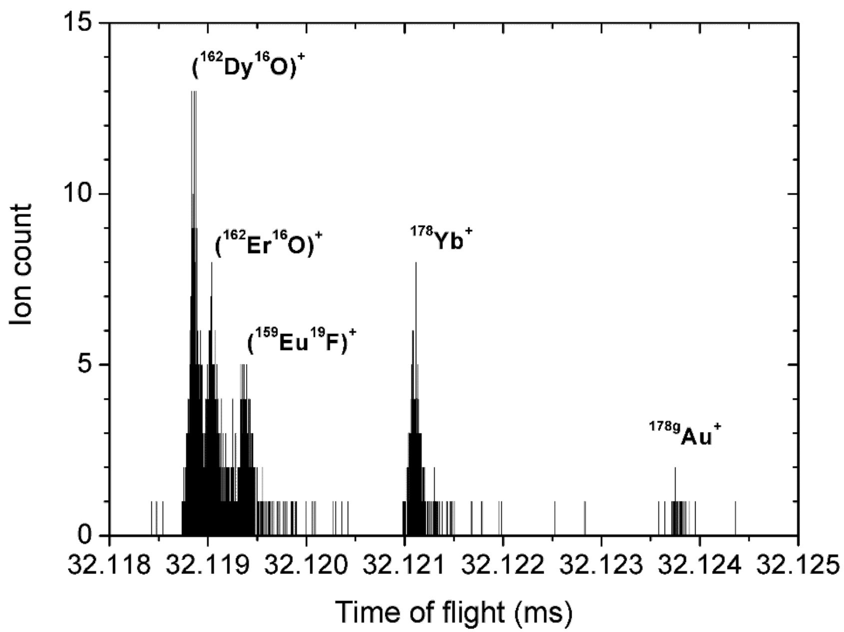


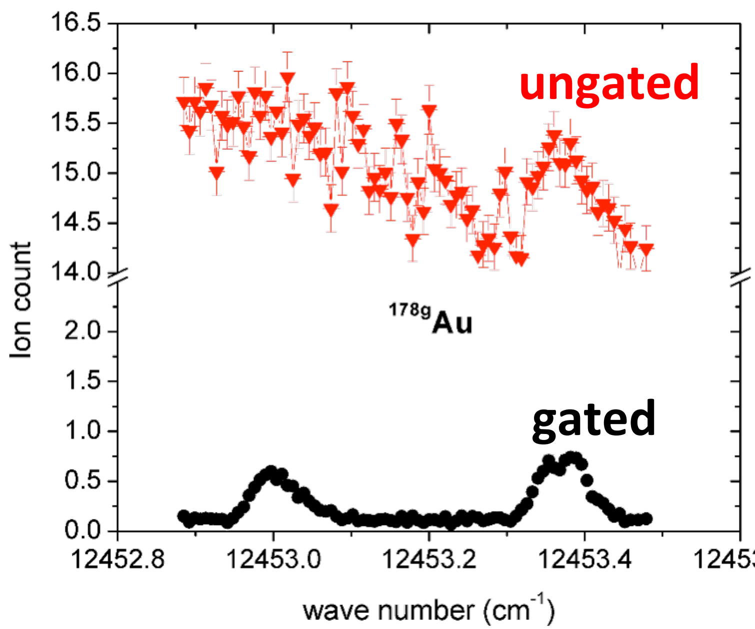


HFS studies in the neutron-deficient lead region



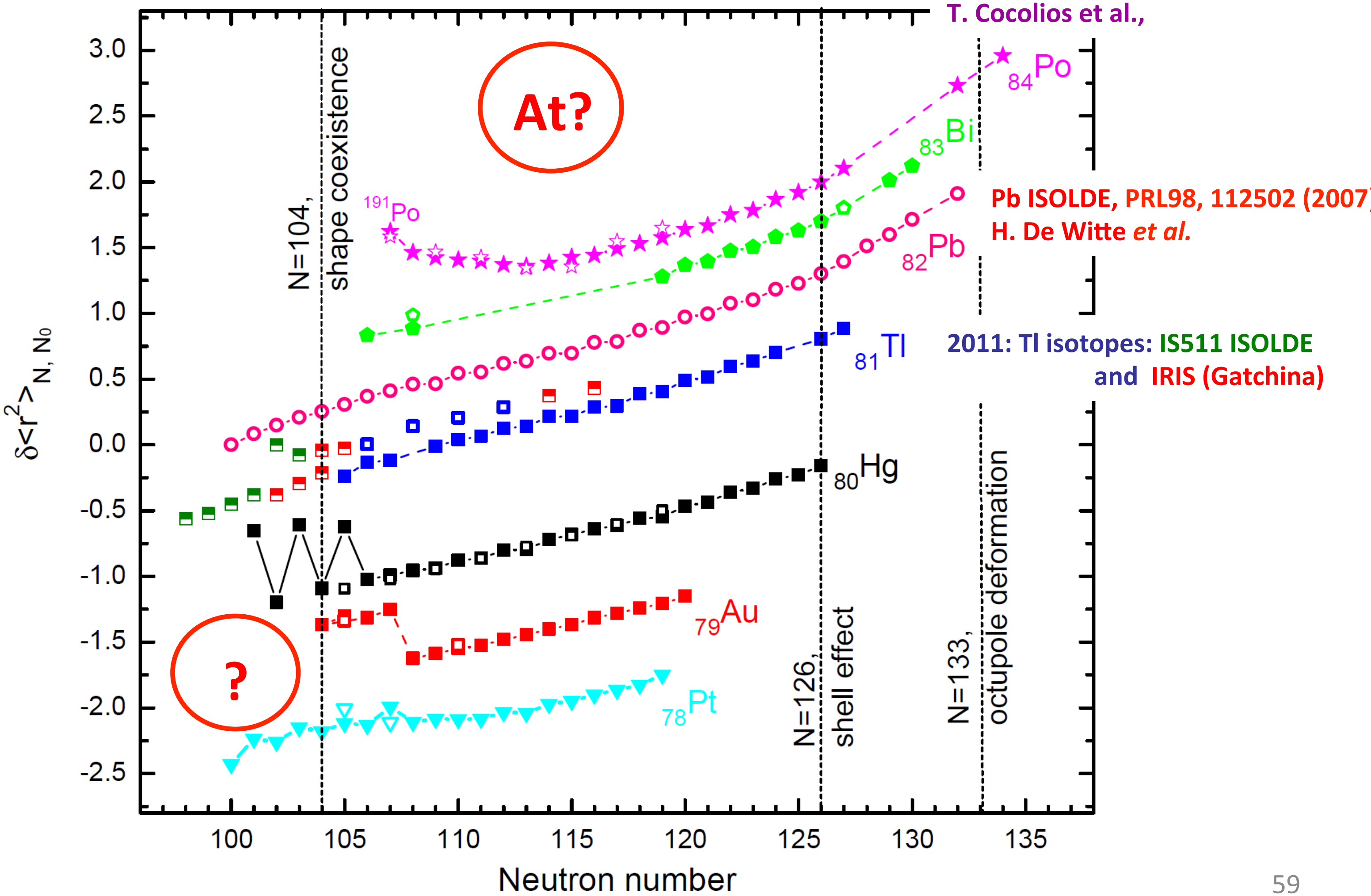
High sensitivity: rare isotopes are accessible.





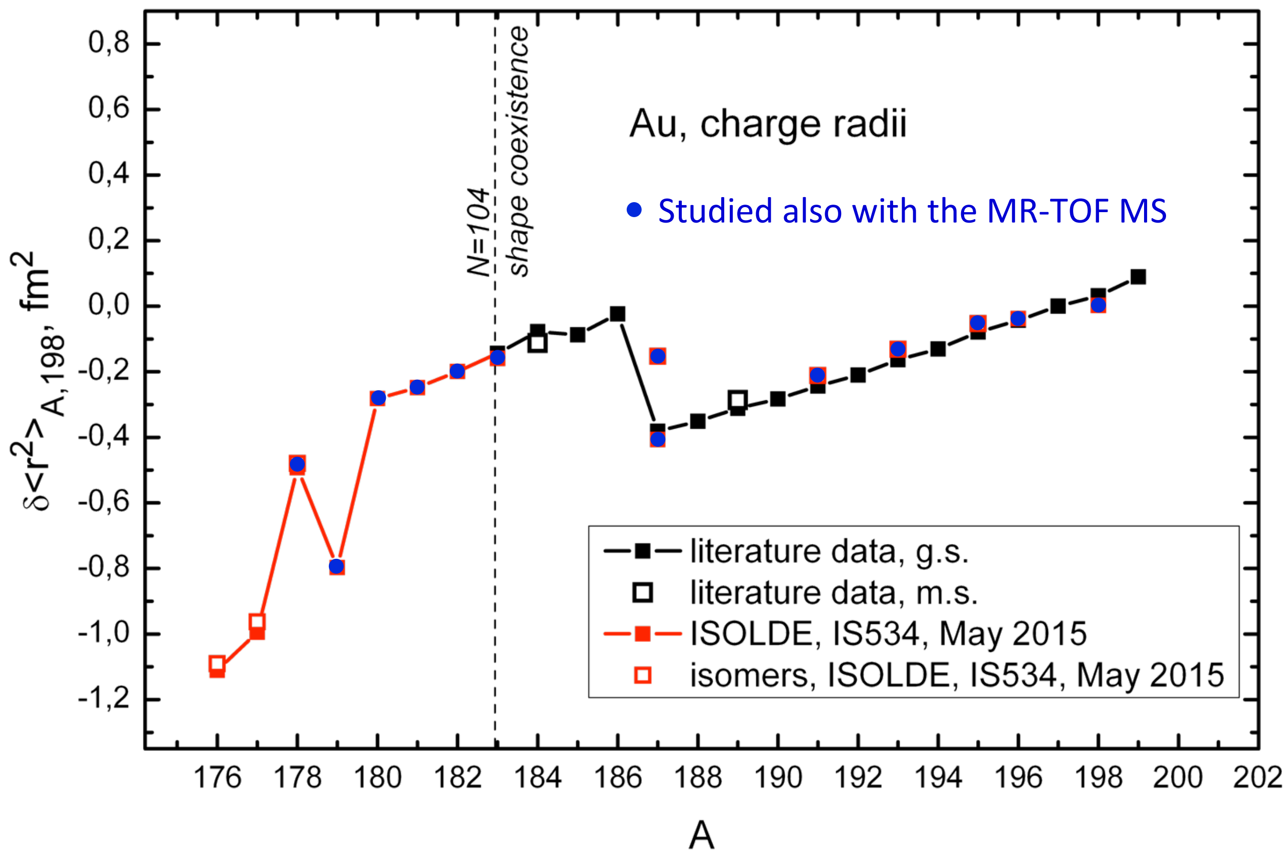
HFS studies in the neutron-deficient lead region

- Situation in 2011:



Charge radii courtesy of A. Barzakh

Charge radii of n-deficient gold isotopes

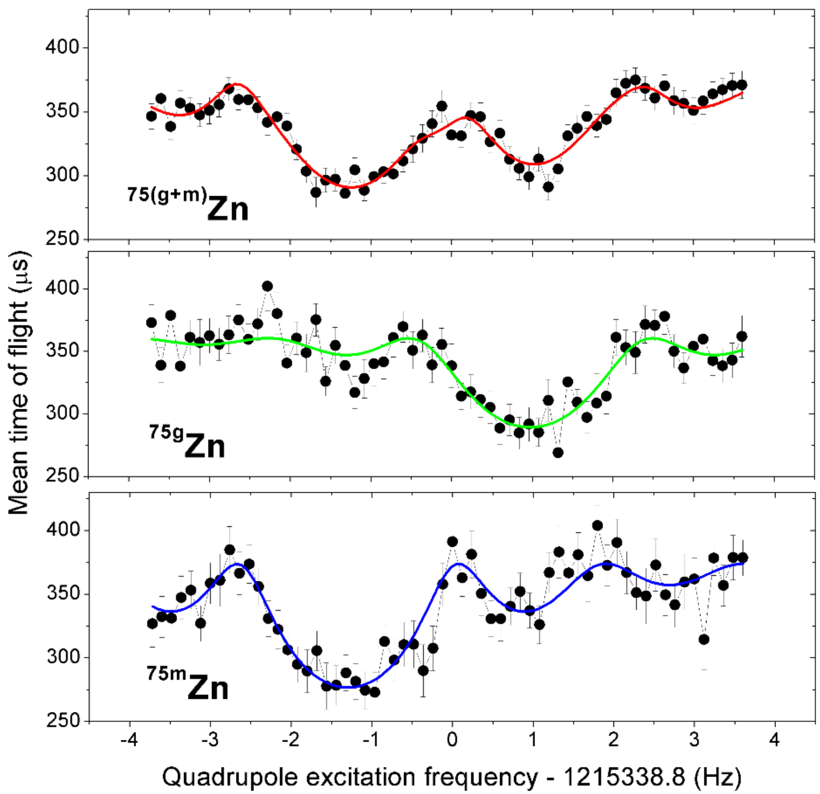


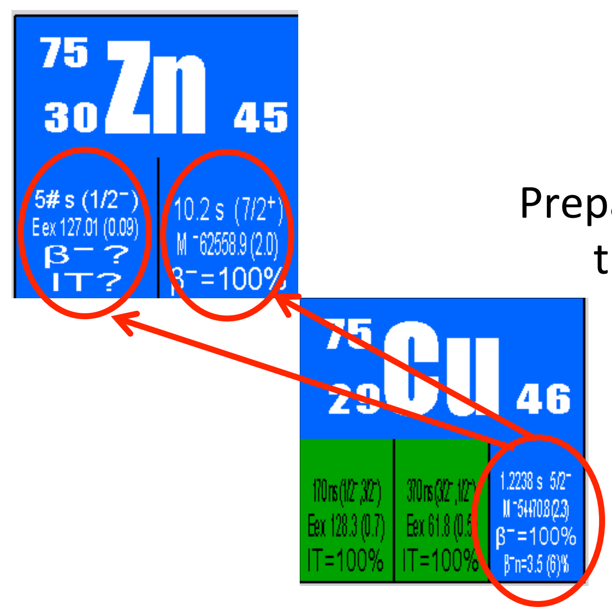
- An end of the region of collectivity.

Charge radii courtesy of A. Barzakh

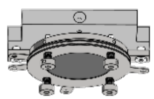
Tests of in-trap decay

- ^{75g,m}Zn produced by in-trap decay of ^{75}Cu ions.
- The two states were subsequently measured with the Penning trap.

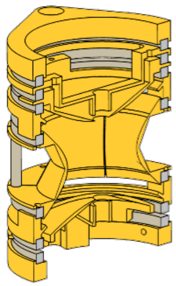




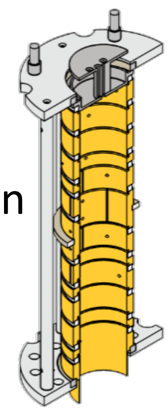
MCP



Precision trap



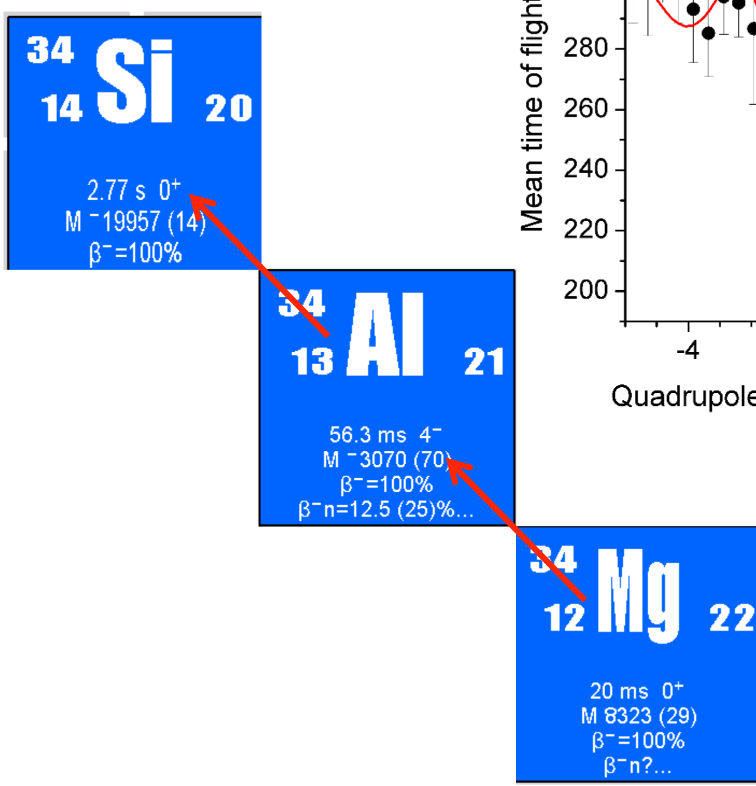
Preparation trap

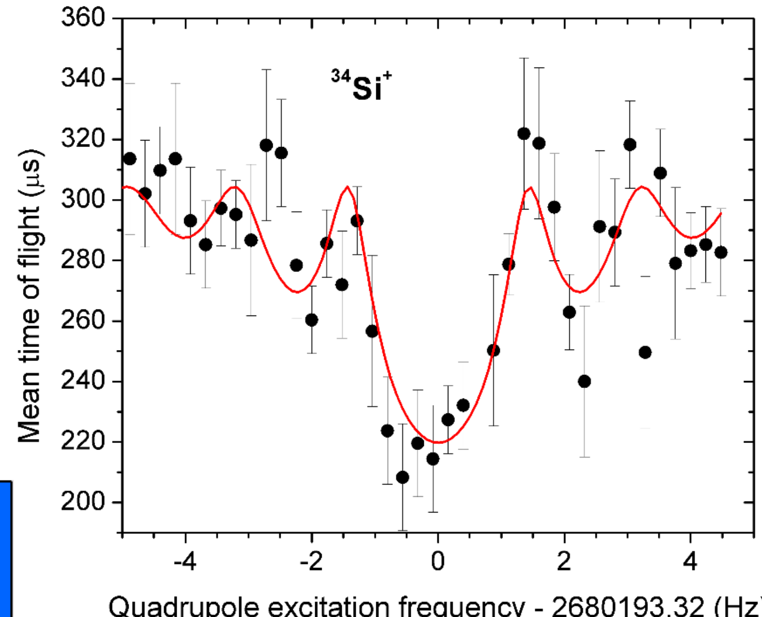


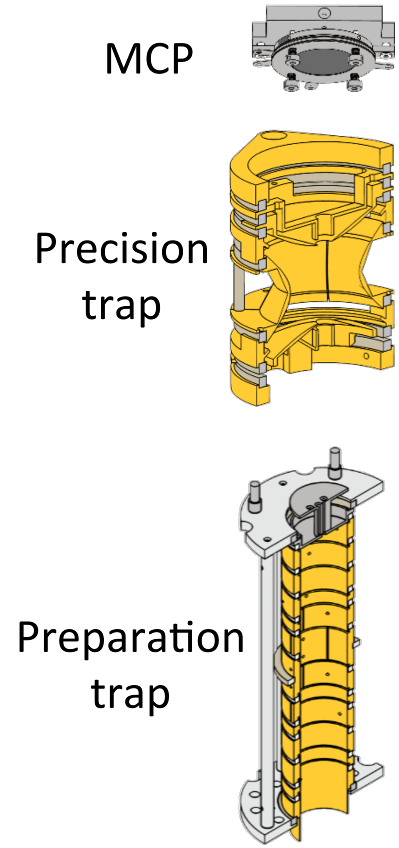
A. Herlert *et al.,* Eur. Phys. J. A **48**, 97 (2012).

Tests of in-trap decay

➢ Double in-trap decay from ^{34}Mg to ^{34}Si was tested.



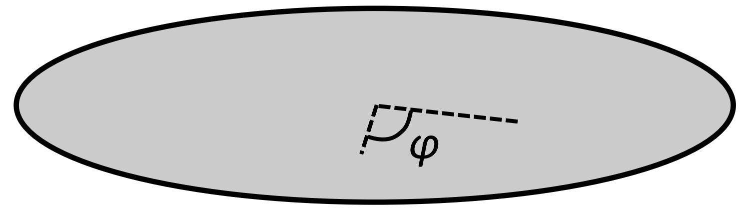




P. Ascher *et al.*, INTC-P-372 (2013).

Phase-imaging ion-cyclotron-resonance technique

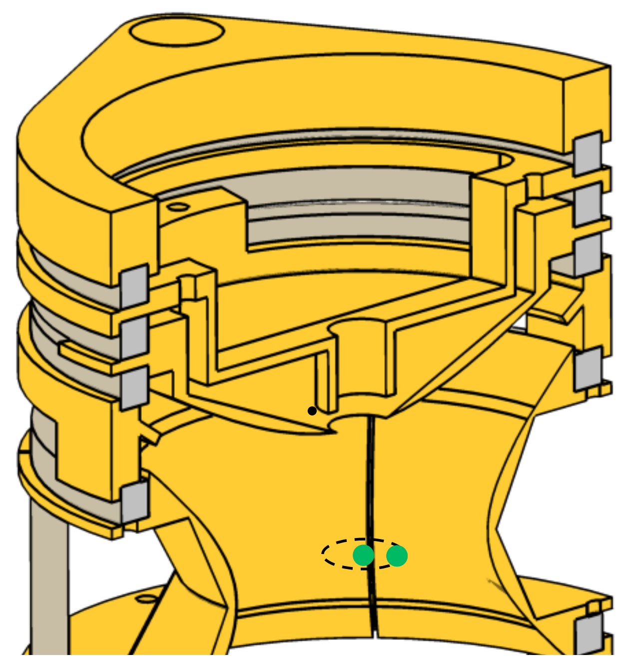
Position-sensitive detector



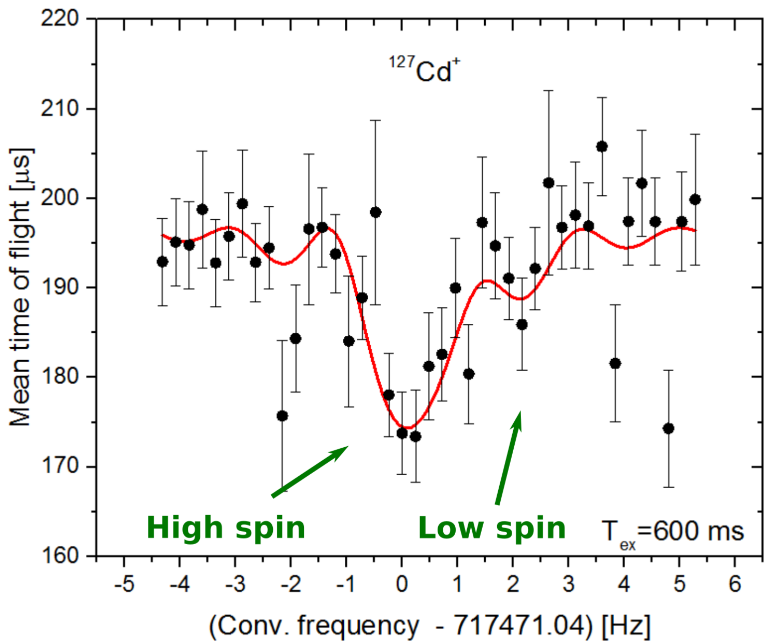
- ✓ No excitation (center position)
- ✓ On radial motion, wait for time *t*
- ✓ On radial motion, wait for time $t + \Delta t$

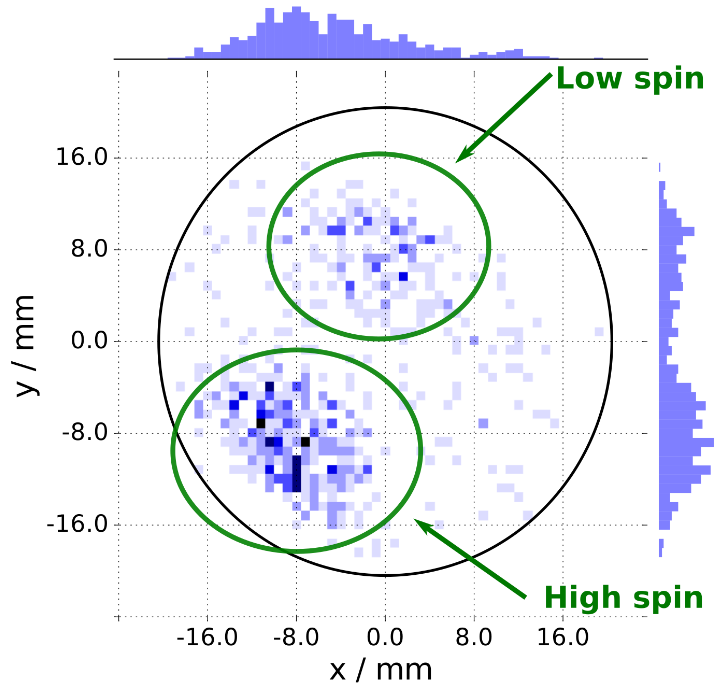
$$\omega = 2\pi n + \varphi / \Delta t$$

- ✓ Has much higher resolving power and precision than TOF-ICR
- ✓ Requires some prior knowledge of the frequency
- ✓ Requires timing stability on ~ns level

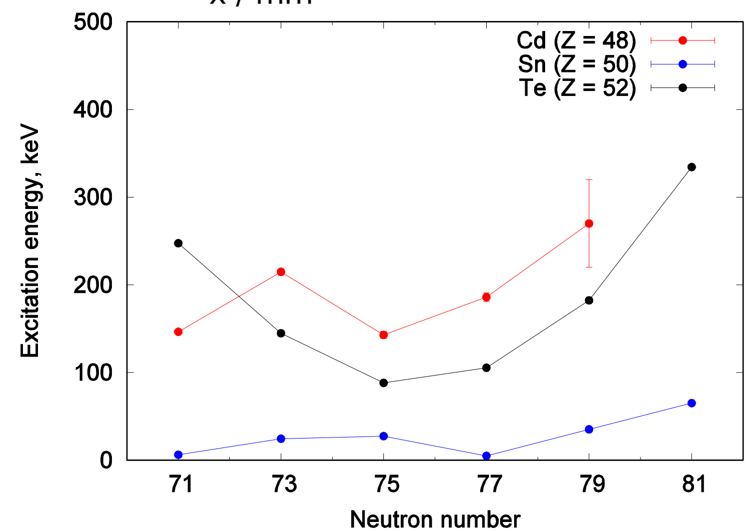


High-resolution isomer separation



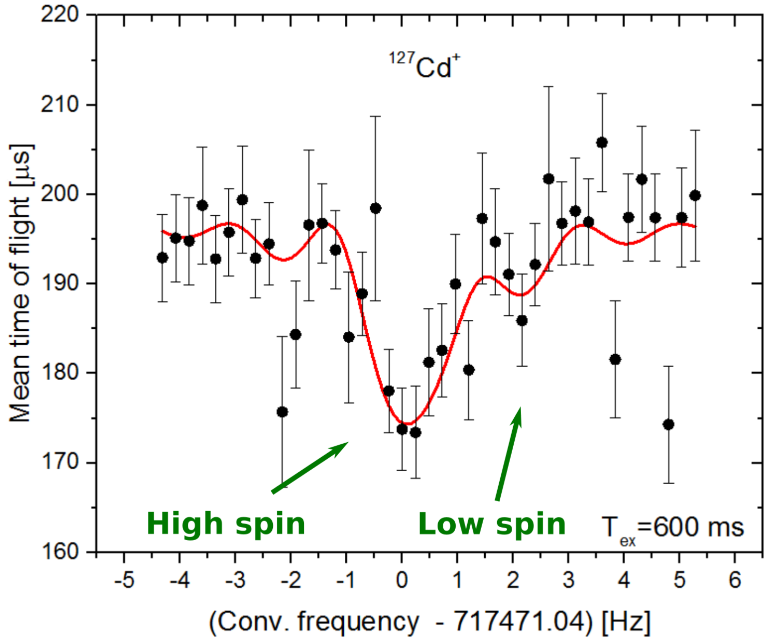


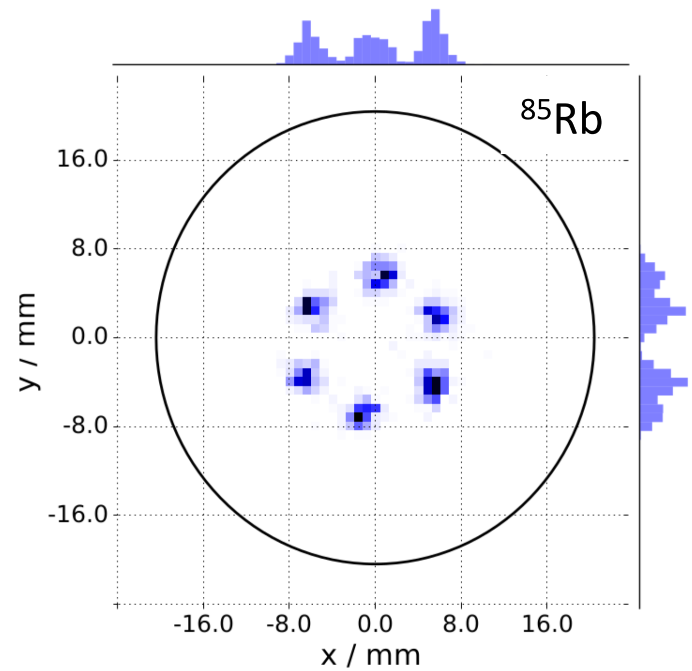
	ISOLTRAP (keV)	AME12 (keV)
$E_{ex}(^{123}Cd)$	149(50)	143(4)
$E_{ex}(^{127}Cd)$	270(50)	0#(100#)



M. König et al., Int. J. Mass Spectrom. 142, 95 (1995);
S. Eliseev, Phys. Rev. Lett. 110, 082501;
A. Kankainen et al. Phys. Rev. C 87, 024307 (2013)

High-resolution isomer separation





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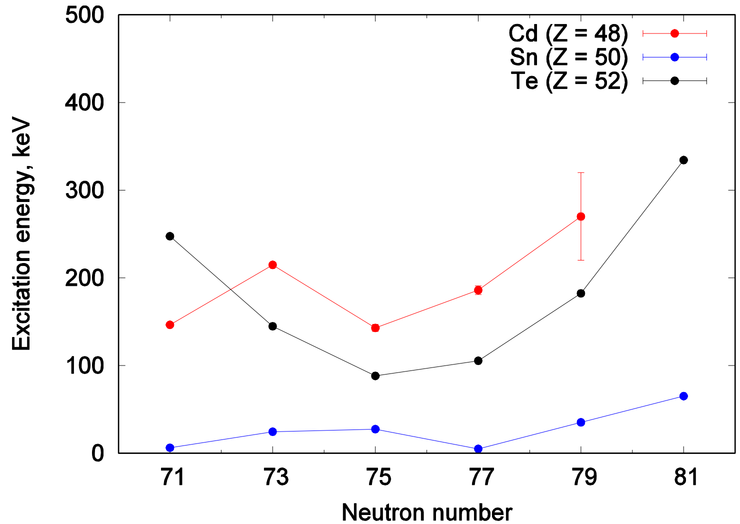

M. König et al., Int. J. Mass Spectrom. 142, 95 (1995);
S. Eliseev, Phys. Rev. Lett. 110, 082501;
A. Kankainen et al. Phys. Rev. C 87, 024307 (2013)

Conclusions

- Ion traps offer a different approach to low-energy nuclear physics.
- ISOLDE is continuously developing techniques for improving the yields and purity of exotic beams.
- ISOLTRAP is in the possession of a wide range of techniques for beam purification, mass measurements and trap-assisted studies.
- There are many ideas to improve and extend the existing ion-trap techniques, as well as to increase their role in low-energy nuclear physics.
- The combination of ISOLDE and ISOLTRAP continues to offer a competitive environment for new physics results.

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GSI

Technische Universität Dresden

CSNSM

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http://isoltrap.web.cern.ch